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(12) **United States Patent**
Caplan

(10) **Patent No.: US 6,831,779 B2**
(45) **Date of Patent: Dec. 14, 2004**

(54) **METHOD AND APPARATUS FOR STABILIZING A HIGH-GAIN, HIGH-POWER SINGLE POLARIZATION EDFA**

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(73) Assignee: **Massachusetts Institute of Technology**, Cambridge, MA (US)

(*) Notice: Subject to any disclaimer, the term of this patent is extended or adjusted under 35 U.S.C. 154(b) by 0 days.

(21) Appl. No.: **09/845,053**

(22) Filed: **Apr. 27, 2001**

(65) **Prior Publication Data**

US 2002/0167721 A1 Nov. 14, 2002

(51) **Int. Cl.**[7] **H01S 3/00**
(52) **U.S. Cl.** **359/347**; 359/333
(58) **Field of Search** 359/347, 333

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Caplan, D.O., et al., "A high–power high–gain single–polarization EDFA", *Lasers and Electro–Optics, 2000* (*CLEO* 2000), CWJ3, pp. 283–284, May 7–12, 2000, ISBN 1–55752–634–6. (Abstract attached).

Caplan, D.O., et al., "High–Sensitivity variable–rate transmit/receive architecture", *IEEE LEOS* '99, TuU 0003, 1999.

Duling, I.N., III, et al., "Single–Polarisation Fibre Amplifier," *Elec. Let.*, 28 (12) : 1126–1128 (1992).

Glassner, David S., et al., "Spatial hole burning in erbium fiber lasers using Faraday rotator mirrors," *OFC '97 Technical Digest*, paper TuN3, pp. 66–67.

Hakimi, F., et al., "High–power single–polarization EDFA with wavelength–multiplexed pumps", *CLEO* '98, CWK1, 1998, pp. 287–288.

Tashiro, Y., et al., "High–power erbium–doped fier amplifier pumped by wavelength multiplexed semiconductor laser diode unit", *Optical Fiber Communication, OFC* '97 Conference on 1997, pp. 107–108.

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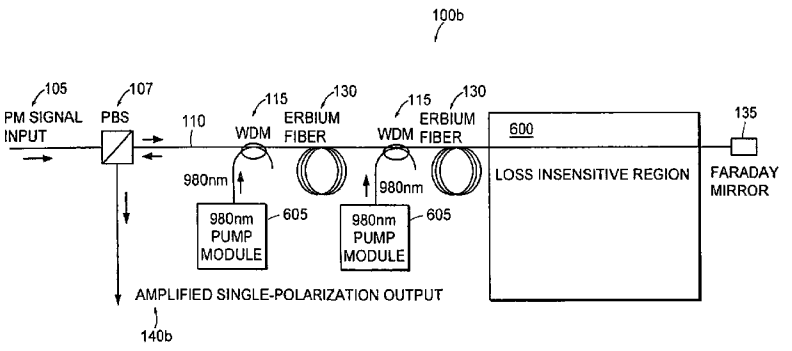
Primary Examiner—Thomas G. Black
Assistant Examiner—Stephen Cunningham
(74) *Attorney, Agent, or Firm*—Hamilton, Brook, Smith & Reynolds, P.C.

(57) **ABSTRACT**

A high-gain, saturated output, double-pass, fault-tolerant optical amplifier has an extended range of stability, output power, and efficiency and fall back modes of operation. The optical amplifier is typically configured in a two-stage polarization maintaining configuration, employing erbium-doped fibers as the gain media in both of the stages. At least one optical element in a loss-insensitive region of the amplifier can have a loss substantially higher than optical elements in the gain paths outside of the loss-insensitive region without substantially reducing the overall output power and efficiency of the amplifier. These elements can influence the amplified signal waveform, spectrum, signal-to-noise ratio, or subsequent performance in an optical network, as well as amplifier characteristics, such as output power, stability, efficiency, and reliability. The optical amplifier is suitable for both free-space and fiber optic network applications.

52 Claims, 33 Drawing Sheets



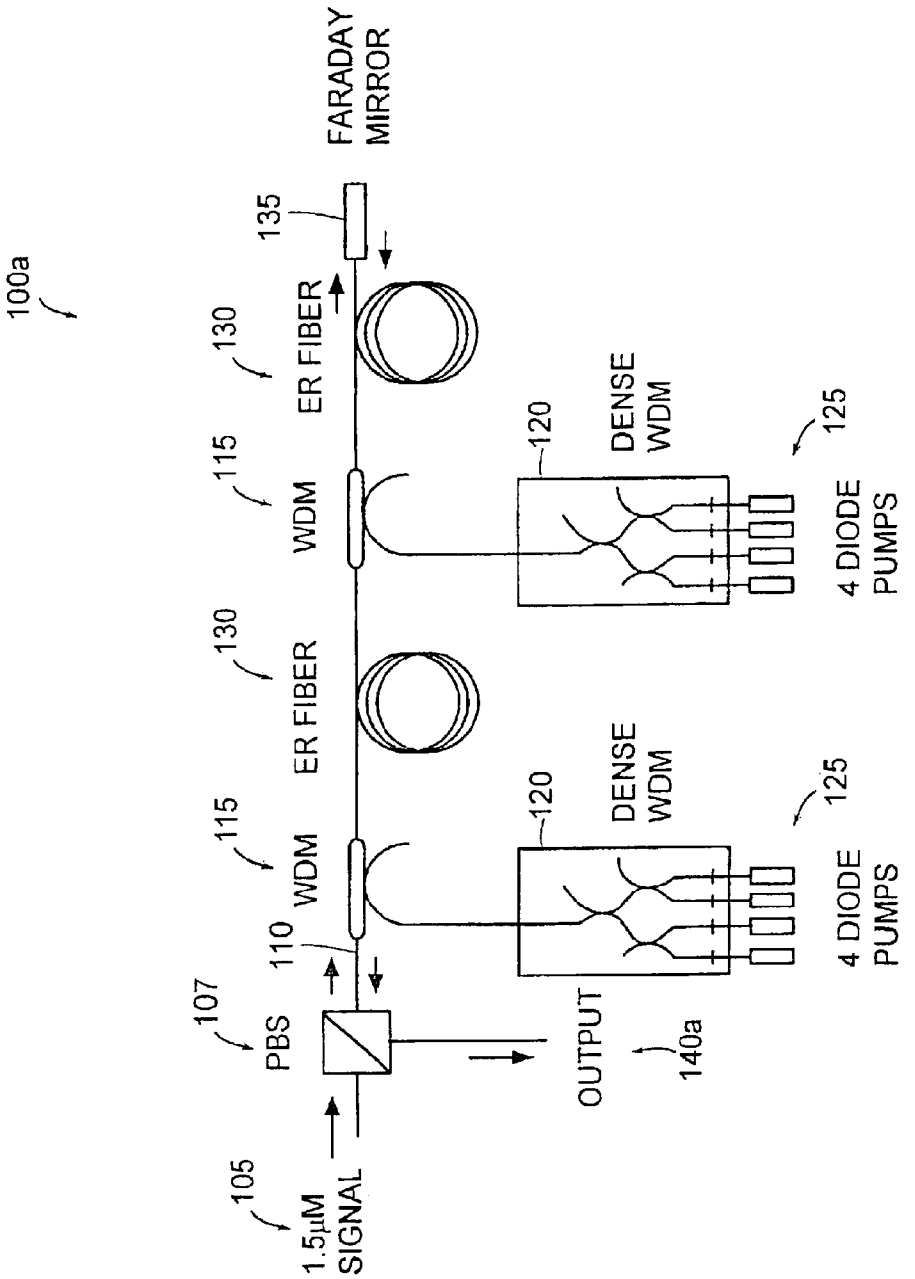


FIG. 1
PRIOR ART

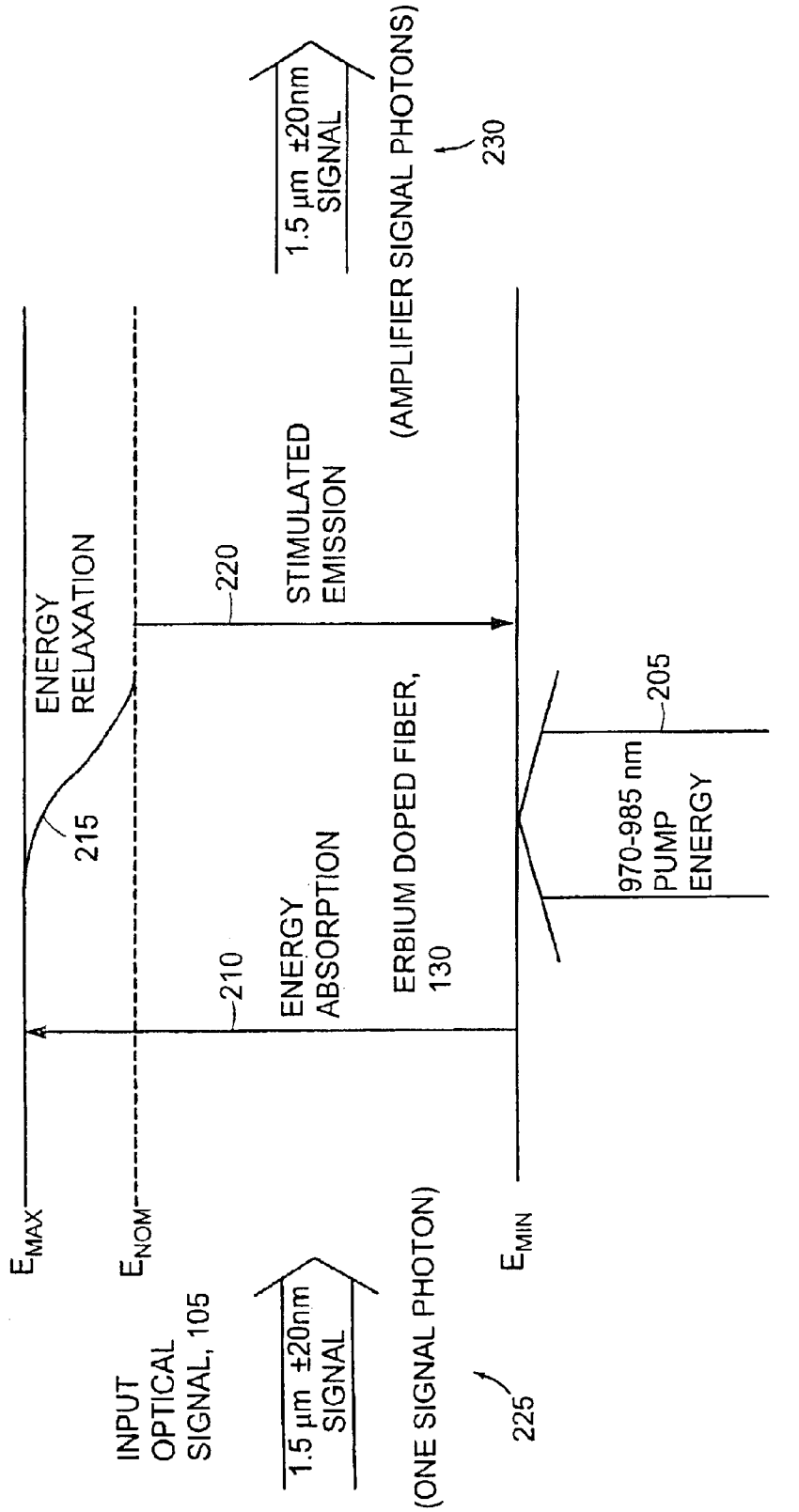


FIG. 2
PRIOR ART

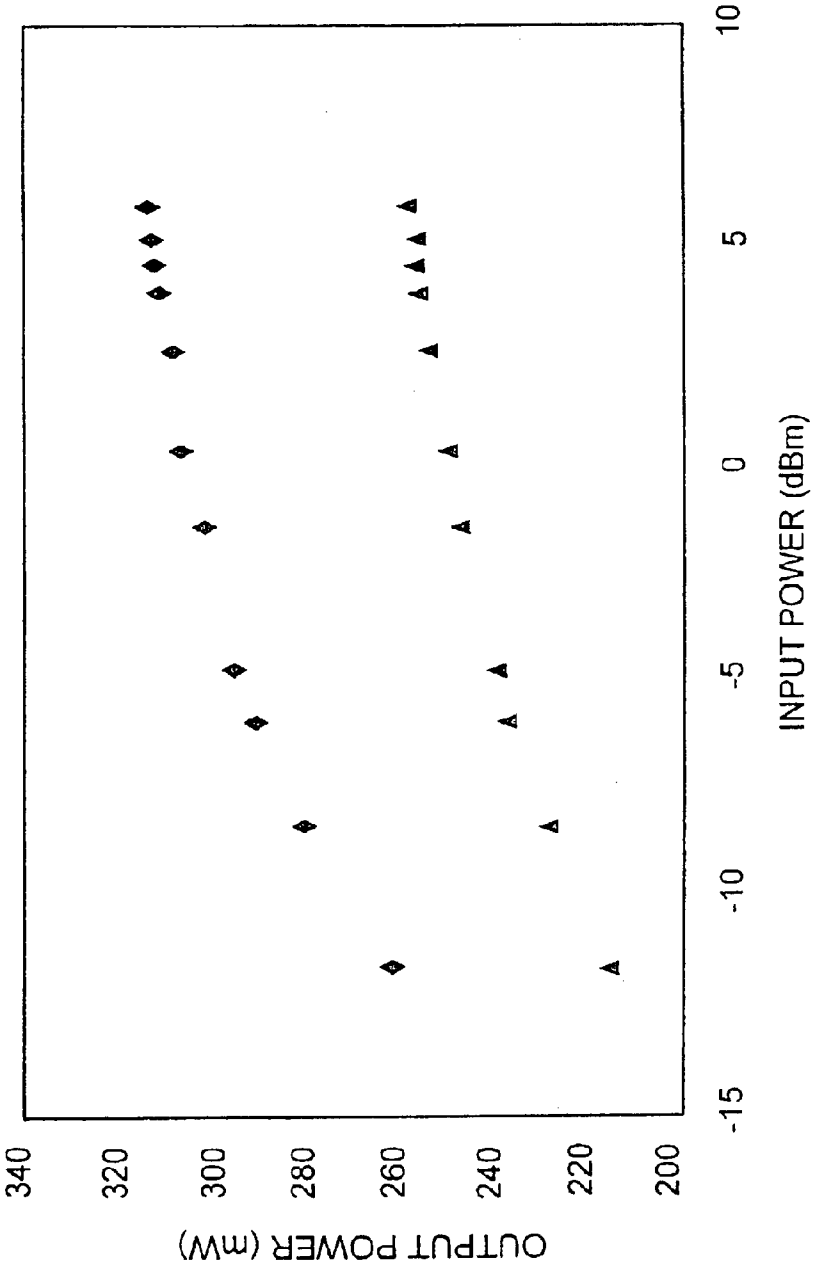


FIG. 3
PRIOR ART

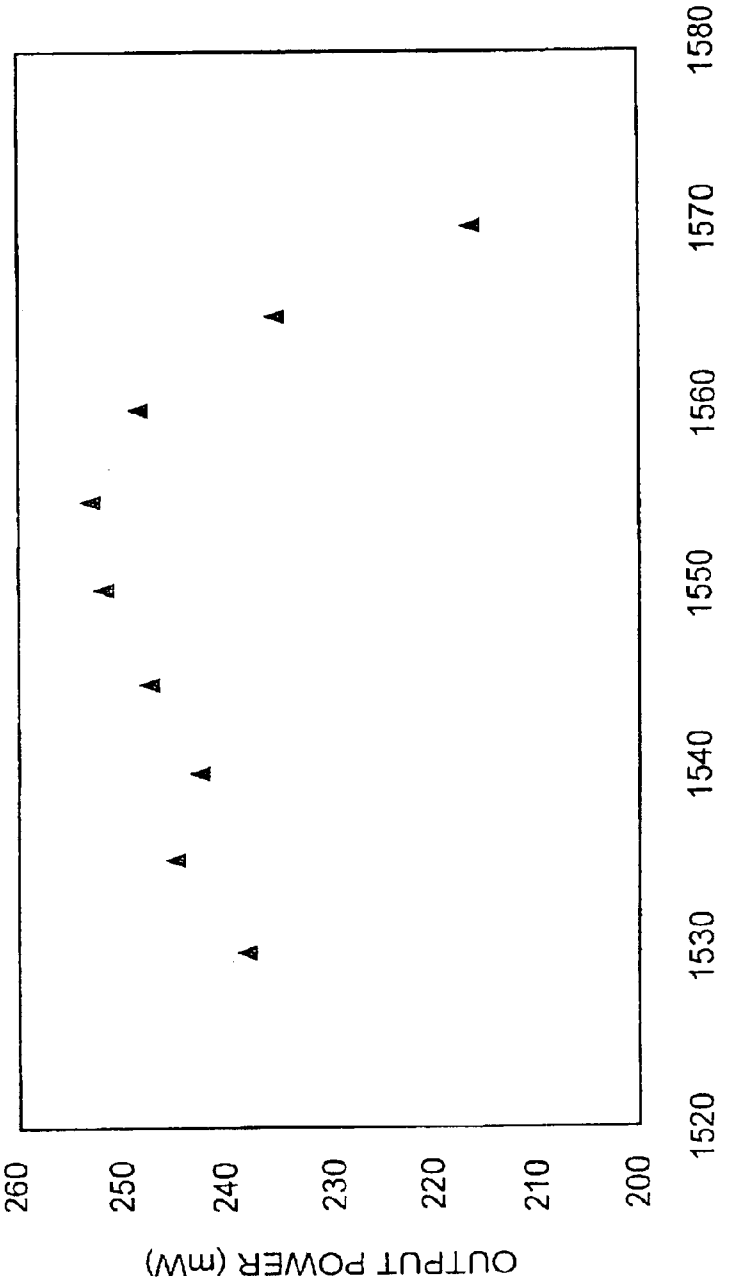


FIG. 4
PRIOR ART

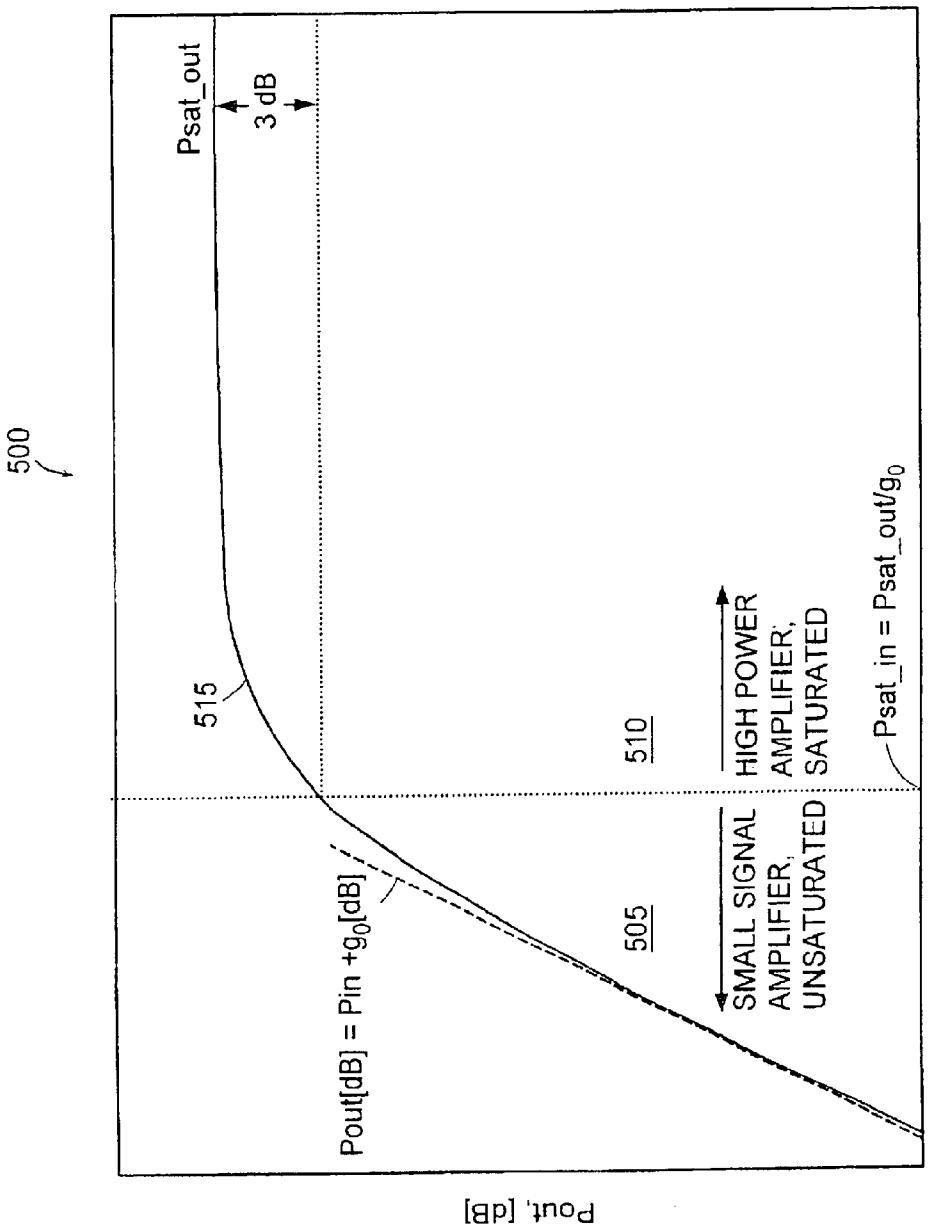

500
Psat_out
3 dB
515
510
505
HIGH POWER AMPLIFIER, SATURATED
SMALL SIGNAL AMPLIFIER, UNSATURATED
Pout[dB] = Pin +g0[dB]
Psat_in = Psat_out/g0
Pin, [dB]
Pout, [dB]

FIG. 5A

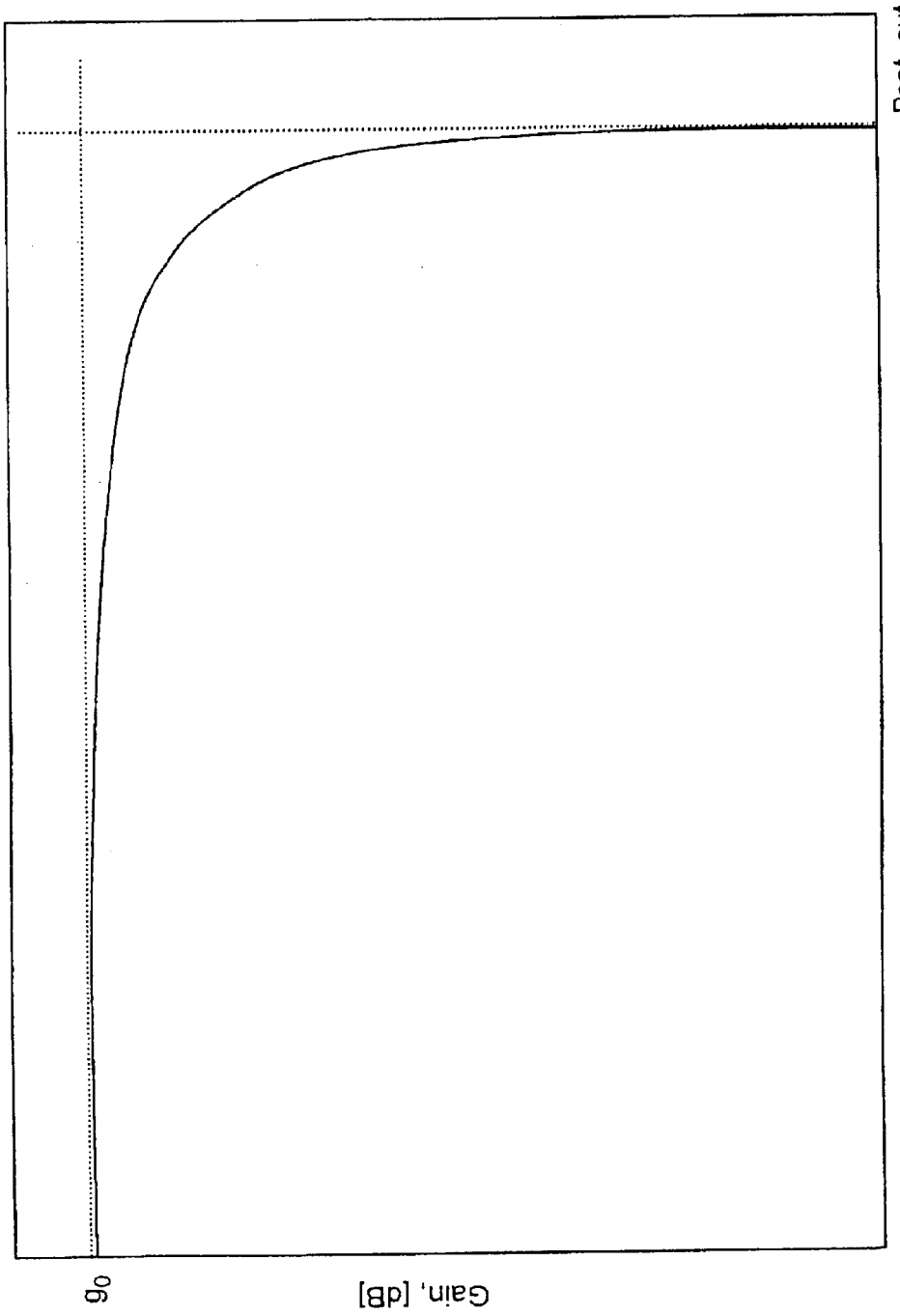


FIG. 5B

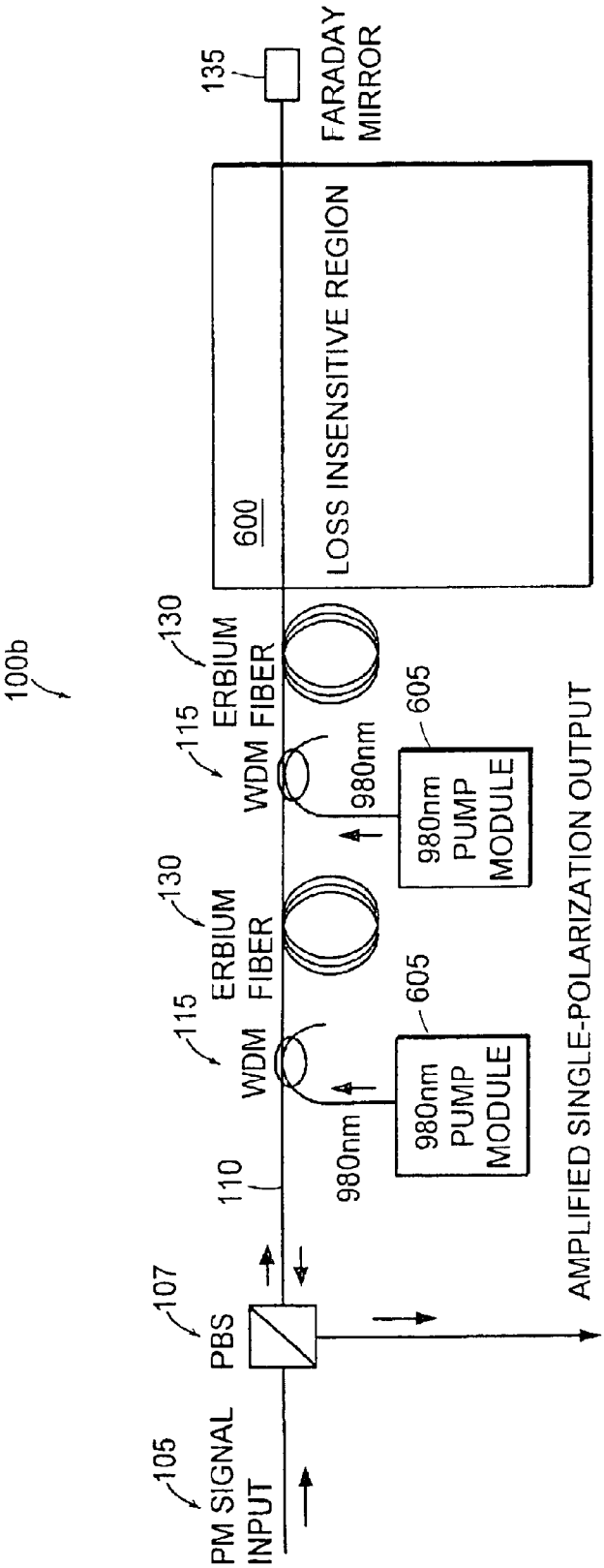

100b
105
PM SIGNAL INPUT
107
PBS
110
115
WDM
980nm
605
980nm PUMP MODULE
130
ERBIUM FIBER
600
LOSS INSENSITIVE REGION
135
FARADAY MIRROR
AMPLIFIED SINGLE-POLARIZATION OUTPUT
140b

FIG. 6

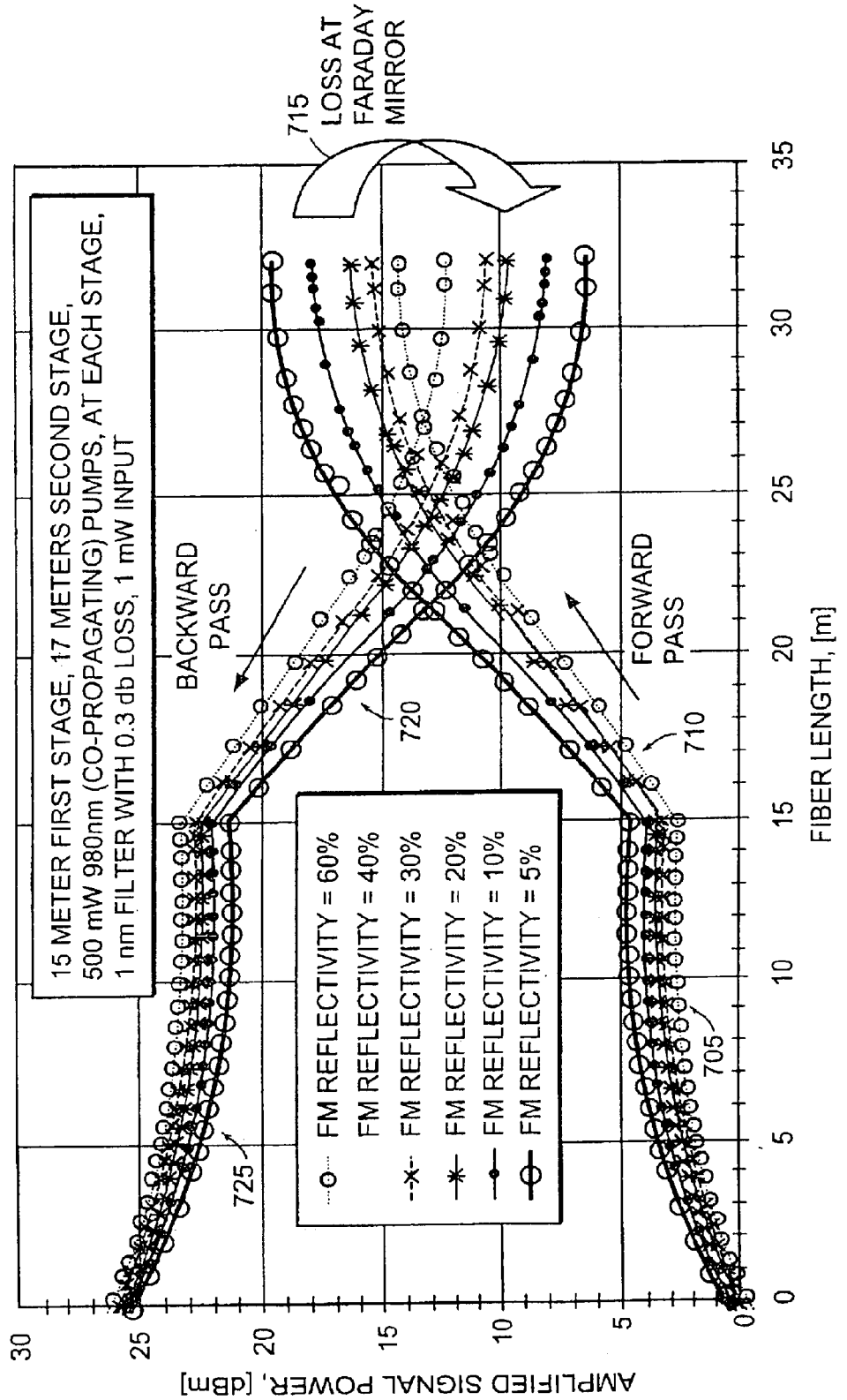

15 METER FIRST STAGE, 17 METERS SECOND STAGE,
500 mW 980nm (CO-PROPAGATING) PUMPS, AT EACH STAGE,
1 nm FILTER WITH 0.3 db LOSS, 1 mW INPUT
715
LOSS AT FARADAY MIRROR
BACKWARD PASS
FORWARD PASS
720
710
705
725
FM REFLECTIVITY = 60%
FM REFLECTIVITY = 40%
FM REFLECTIVITY = 30%
FM REFLECTIVITY = 20%
FM REFLECTIVITY = 10%
FM REFLECTIVITY = 5%
AMPLIFIED SIGNAL POWER, [dBm]
FIBER LENGTH, [m]
0
5
10
15
20
25
30
35

FIG. 7A

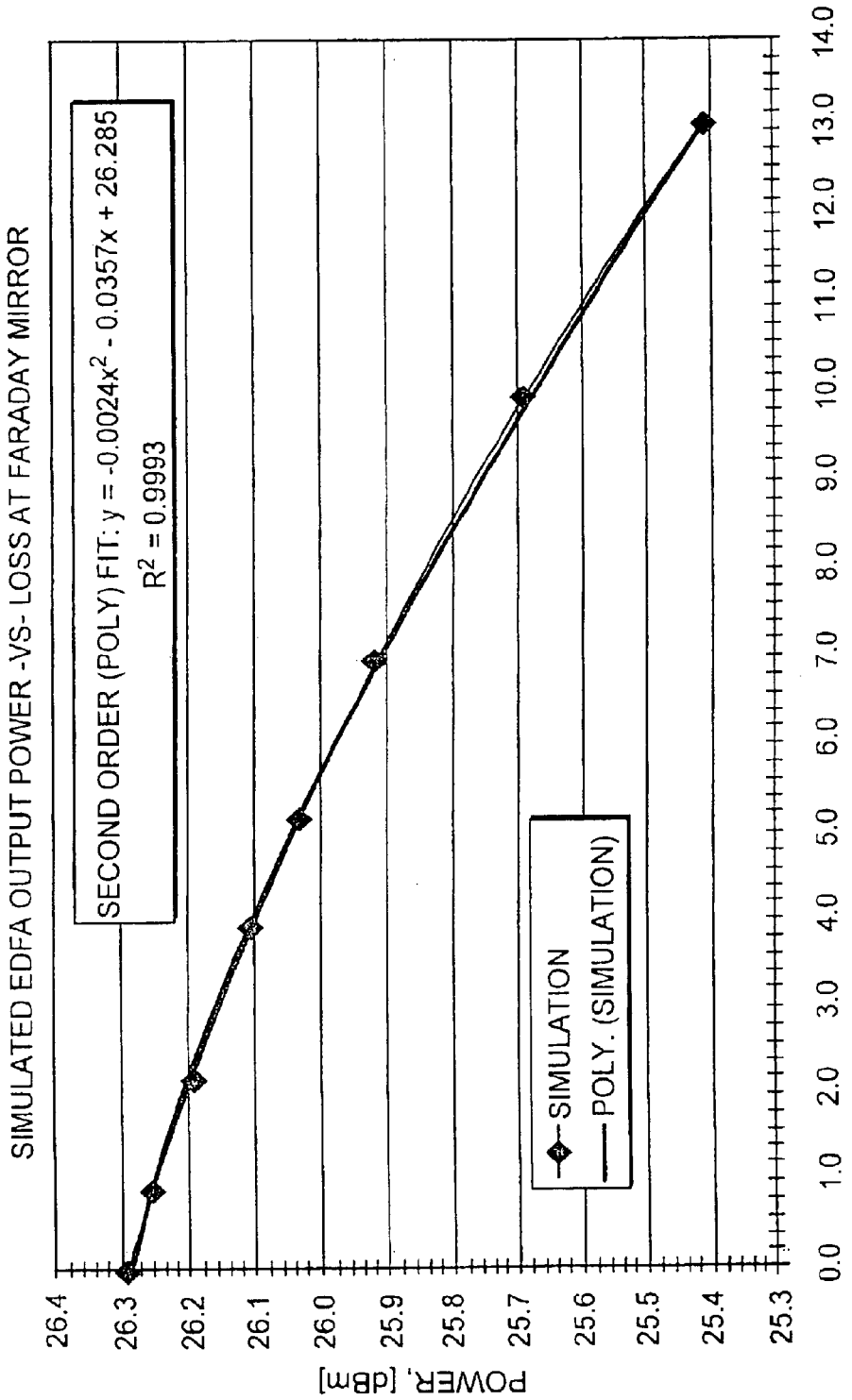

SIMULATED EDFA OUTPUT POWER -VS- LOSS AT FARADAY MIRROR
SECOND ORDER (POLY) FIT: y = -0.0024x² - 0.0357x + 26.285
R² = 0.9993
SIMULATION
POLY. (SIMULATION)
POWER, [dBm]
REFLECTION LOSS, [dBm]
26.4
26.3
26.2
26.1
26.0
25.9
25.8
25.7
25.6
25.5
25.4
25.3
0.0
1.0
2.0
3.0
4.0
5.0
6.0
7.0
8.0
9.0
10.0
11.0
12.0
13.0
14.0

FIG. 7B

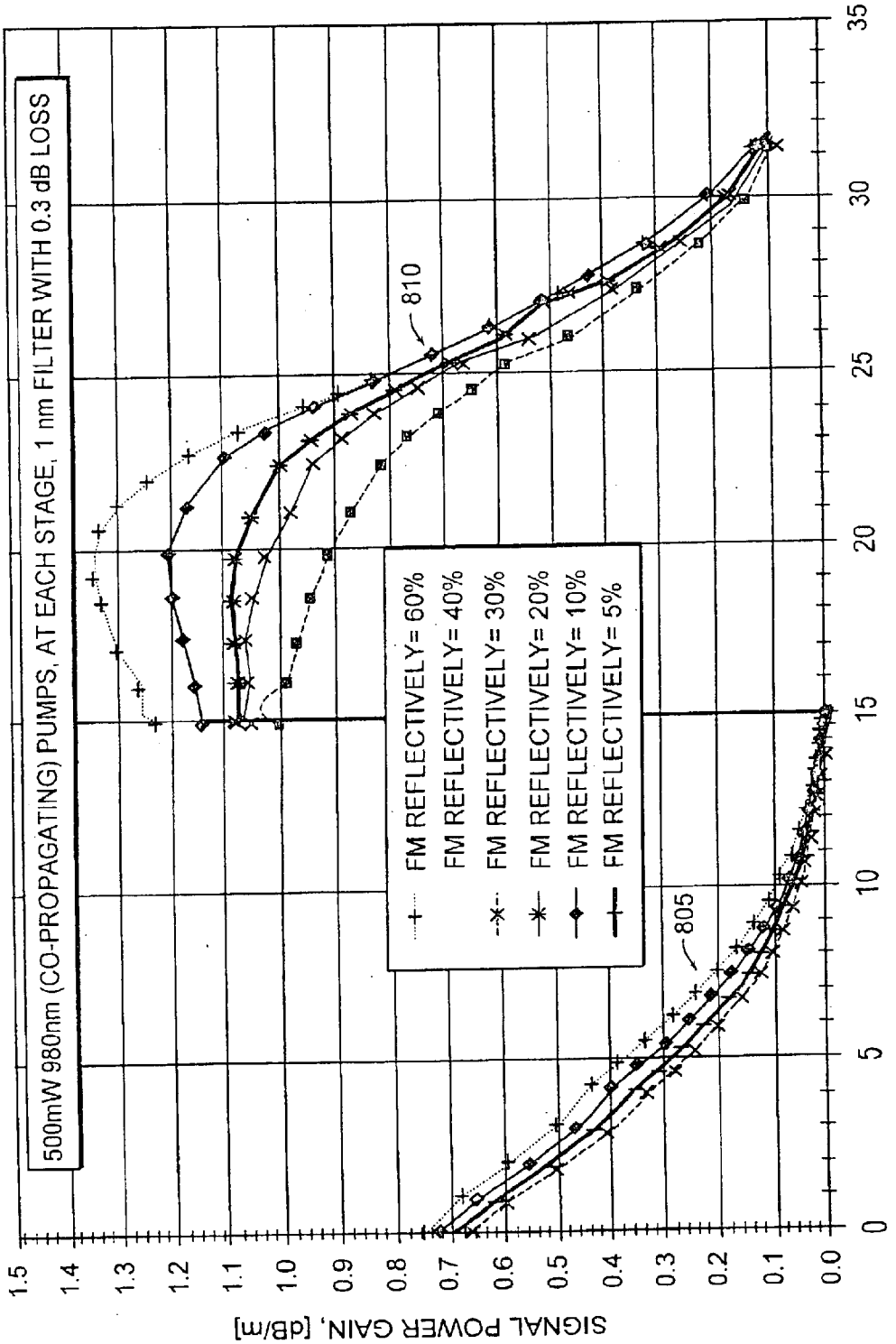

500mW 980nm (CO-PROPAGATING) PUMPS, AT EACH STAGE, 1 nm FILTER WITH 0.3 dB LOSS
FM REFLECTIVELY= 60%
FM REFLECTIVELY= 40%
FM REFLECTIVELY= 30%
FM REFLECTIVELY= 20%
FM REFLECTIVELY= 10%
FM REFLECTIVELY= 5%
810
805
SIGNAL POWER GAIN, [dB/m]
FIBER LENGTH, [m]
0.0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1.0
1.1
1.2
1.3
1.4
1.5
0
5
10
15
20
25
30
35

FIG. 8

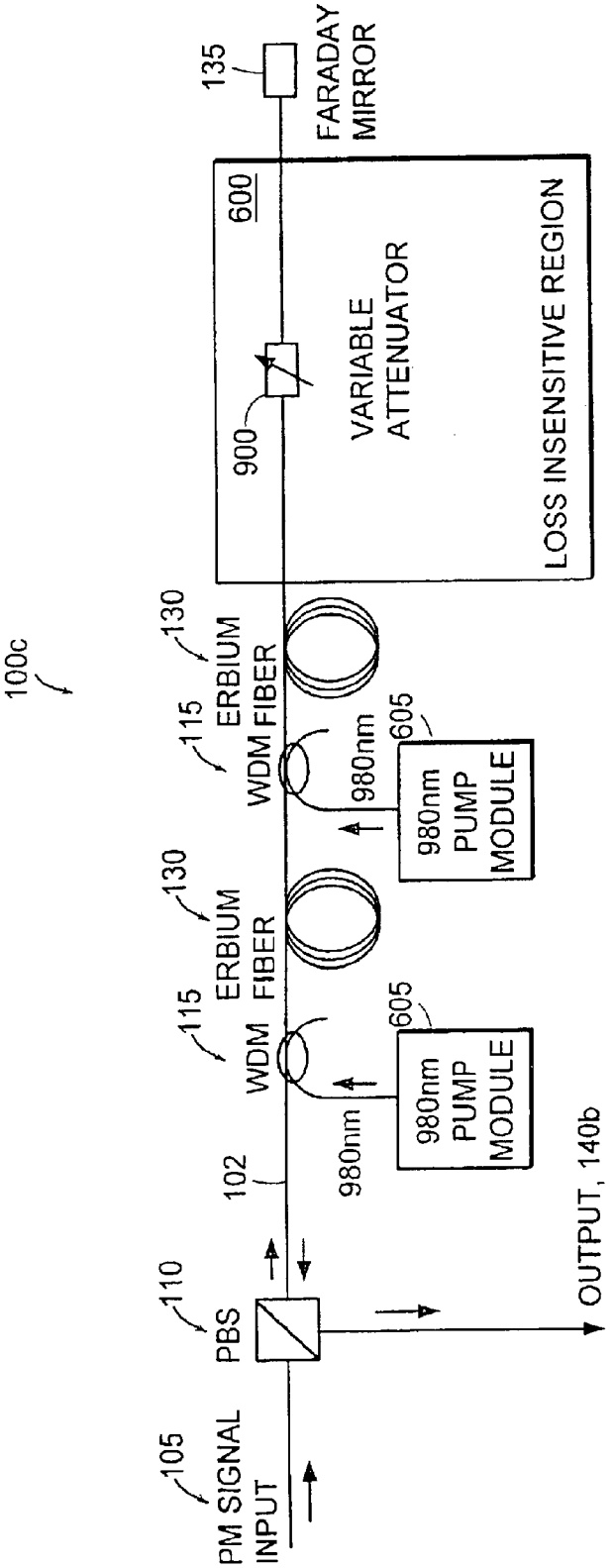

100c
105
PM SIGNAL INPUT
110
PBS
102
115
WDM
130
ERBIUM FIBER
980nm
605
980nm PUMP MODULE
115
WDM
130
ERBIUM FIBER
980nm
605
980nm PUMP MODULE
OUTPUT, 140b
900
VARIABLE ATTENUATOR
600
LOSS INSENSITIVE REGION
135
FARADAY MIRROR

FIG. 9A

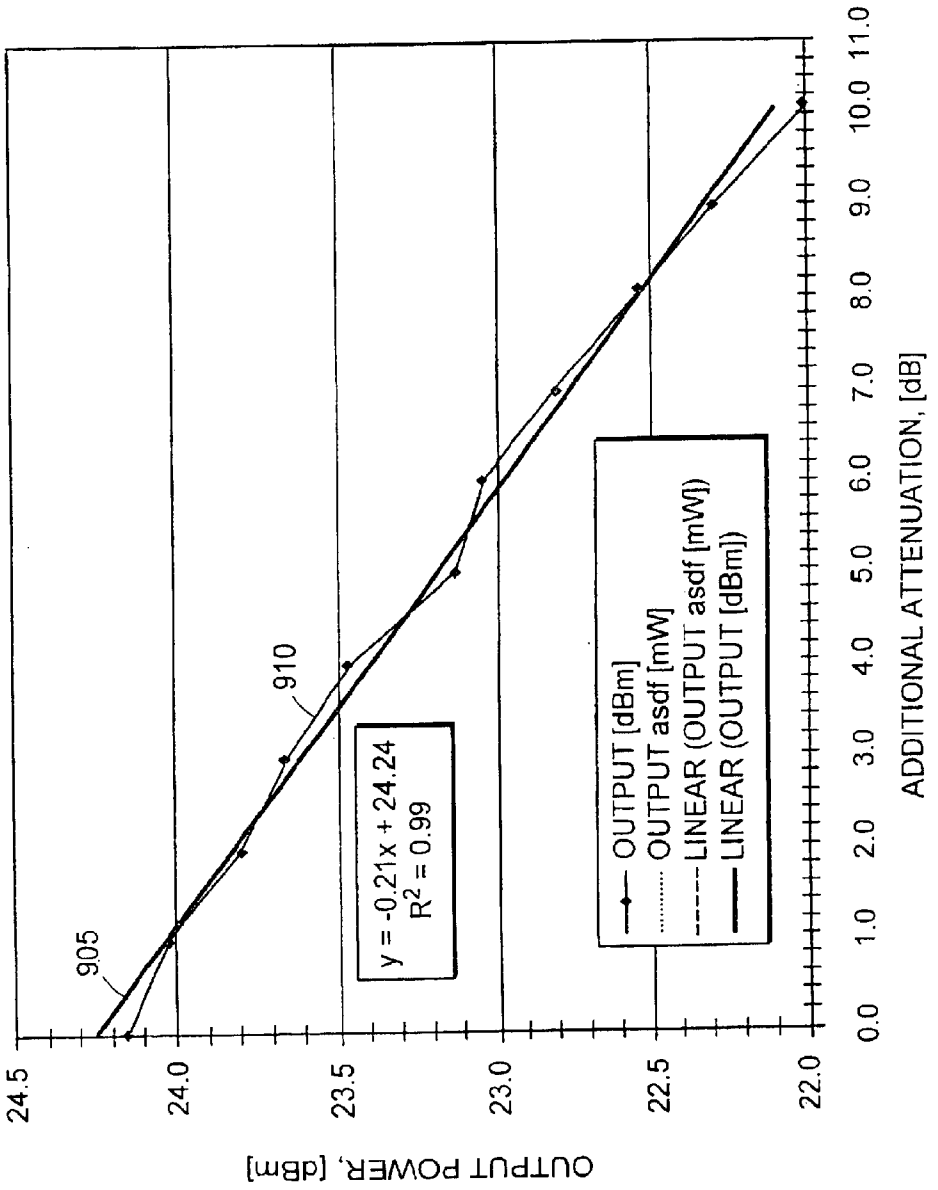

OUTPUT POWER, [dBm]
24.5
24.0
23.5
23.0
22.5
22.0
0.0
1.0
2.0
3.0
4.0
5.0
6.0
7.0
8.0
9.0
10.0
11.0
ADDITIONAL ATTENUATION, [dB]
905
910
y = -0.21x + 24.24
R2 = 0.99
OUTPUT [dBm]
OUTPUT asdf [mW]
LINEAR (OUTPUT asdf [mW])
LINEAR (OUTPUT [dBm])

FIG. 9B

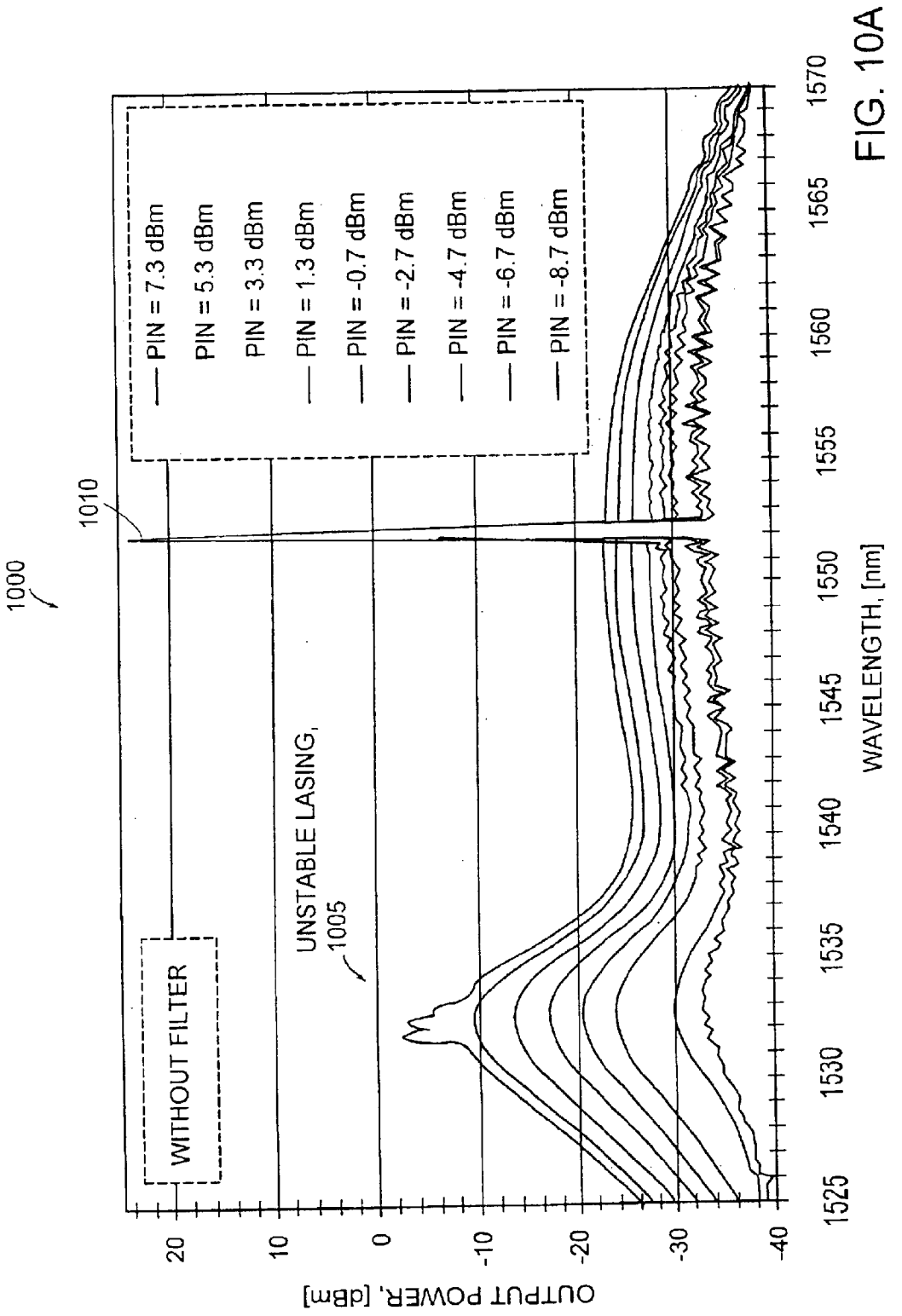

1000
1010
WITHOUT FILTER
UNSTABLE LASING,
1005
PIN = 7.3 dBm
PIN = 5.3 dBm
PIN = 3.3 dBm
PIN = 1.3 dBm
PIN = -0.7 dBm
PIN = -2.7 dBm
PIN = -4.7 dBm
PIN = -6.7 dBm
PIN = -8.7 dBm
OUTPUT POWER, [dBm]
20
10
0
-10
-20
-30
-40
1525
1530
1535
1540
1545
1550
1555
1560
1565
1570
WAVELENGTH, [nm]

FIG. 10A

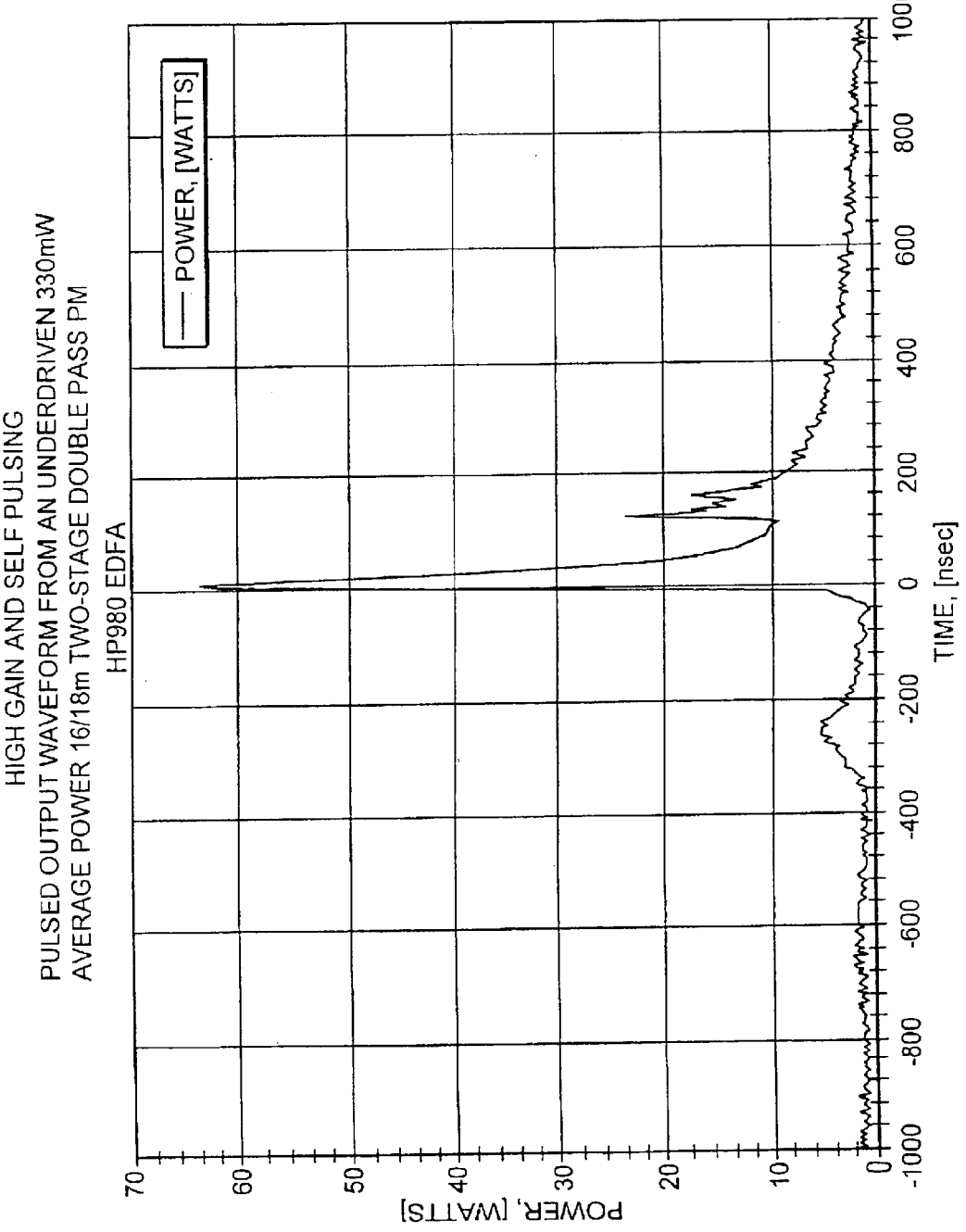

HIGH GAIN AND SELF PULSING
PULSED OUTPUT WAVEFORM FROM AN UNDERDRIVEN 330mW
AVERAGE POWER 16/18m TWO-STAGE DOUBLE PASS PM
HP980 EDFA
POWER, [WATTS]
70
60
50
40
30
20
10
0
-1000
-800
-600
-400
-200
0
200
400
600
800
1000
TIME, [nsec]

FIG. 10B

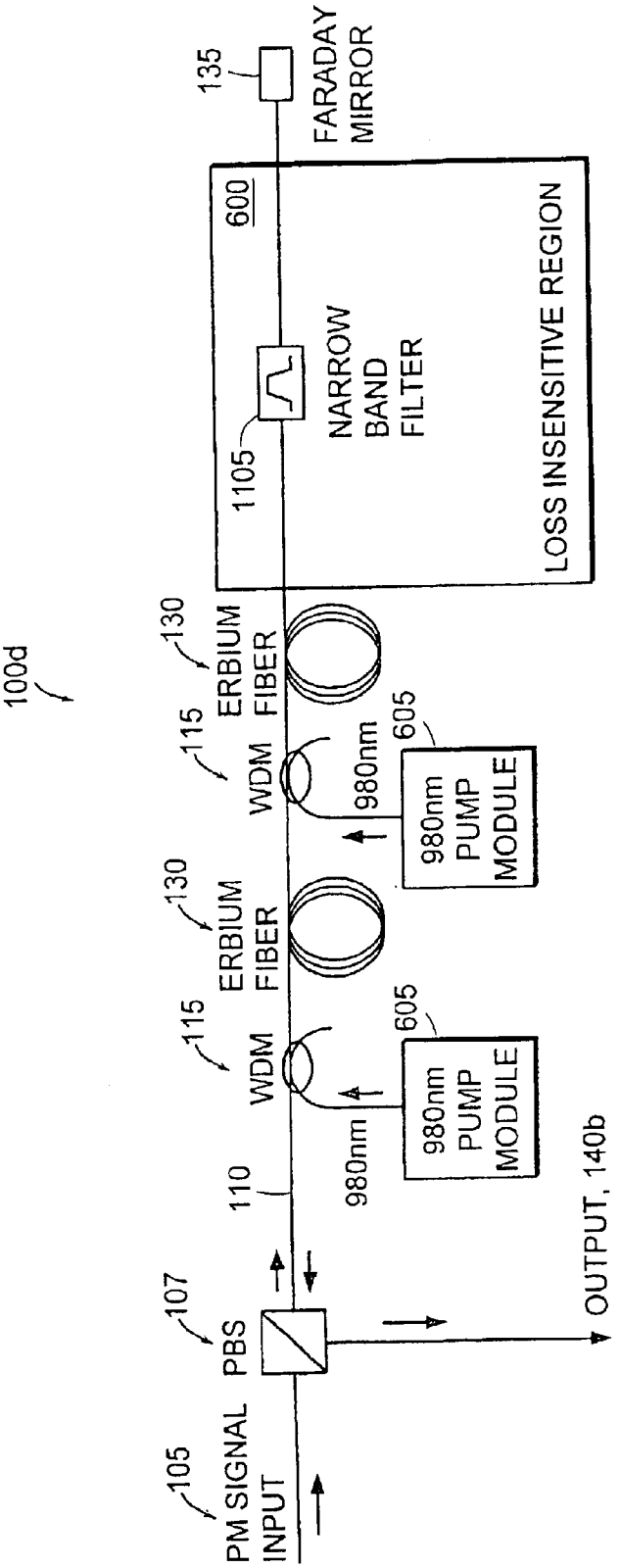

100d
105
PM SIGNAL INPUT
107
PBS
110
115
WDM
130
ERBIUM FIBER
980nm
605
980nm PUMP MODULE
115
WDM
130
ERBIUM FIBER
980nm
605
980nm PUMP MODULE
OUTPUT, 140b
600
1105
NARROW BAND FILTER
LOSS INSENSITIVE REGION
135
FARADAY MIRROR

FIG. 11A

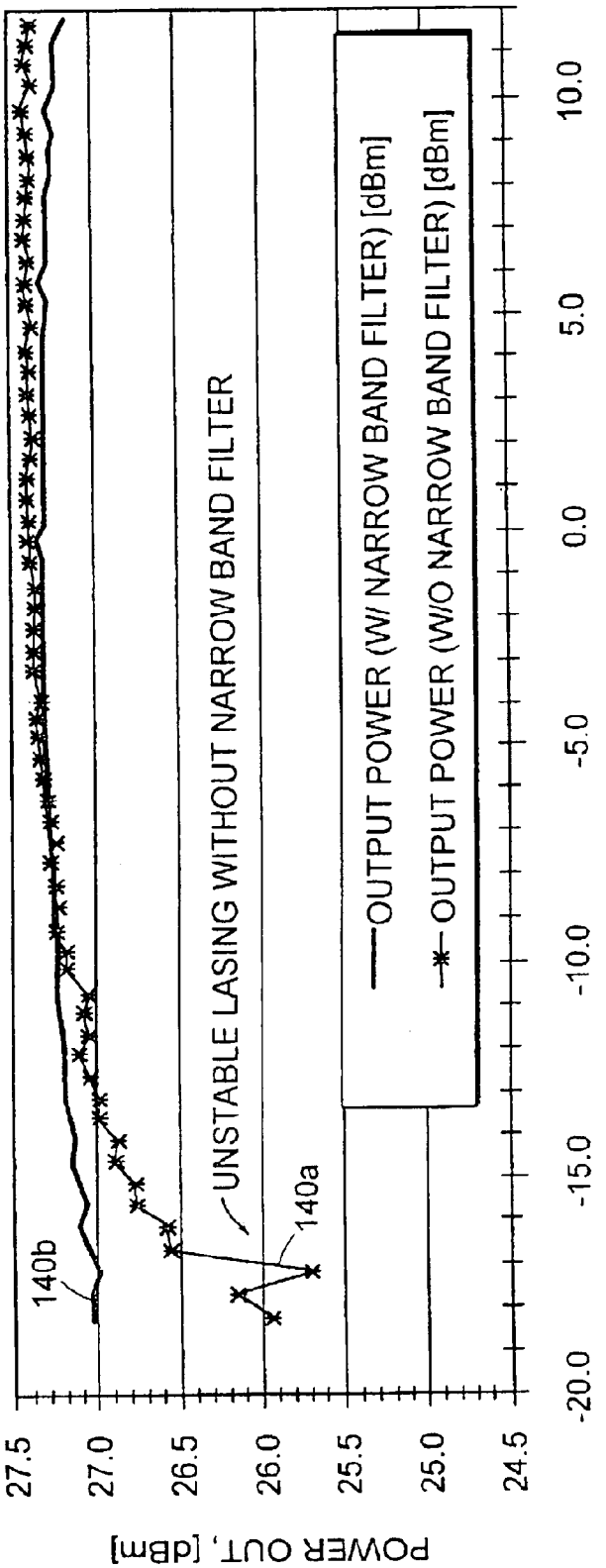

POWER OUT, [dBm]
27.5
27.0
26.5
26.0
25.5
25.0
24.5
-20.0
-15.0
-10.0
-5.0
0.0
5.0
10.0
POWER IN, [dBm]
OUTPUT POWER (W/ NARROW BAND FILTER) [dBm]
OUTPUT POWER (W/O NARROW BAND FILTER) [dBm]
UNSTABLE LASING WITHOUT NARROW BAND FILTER
140a
140b

FIG. 11B

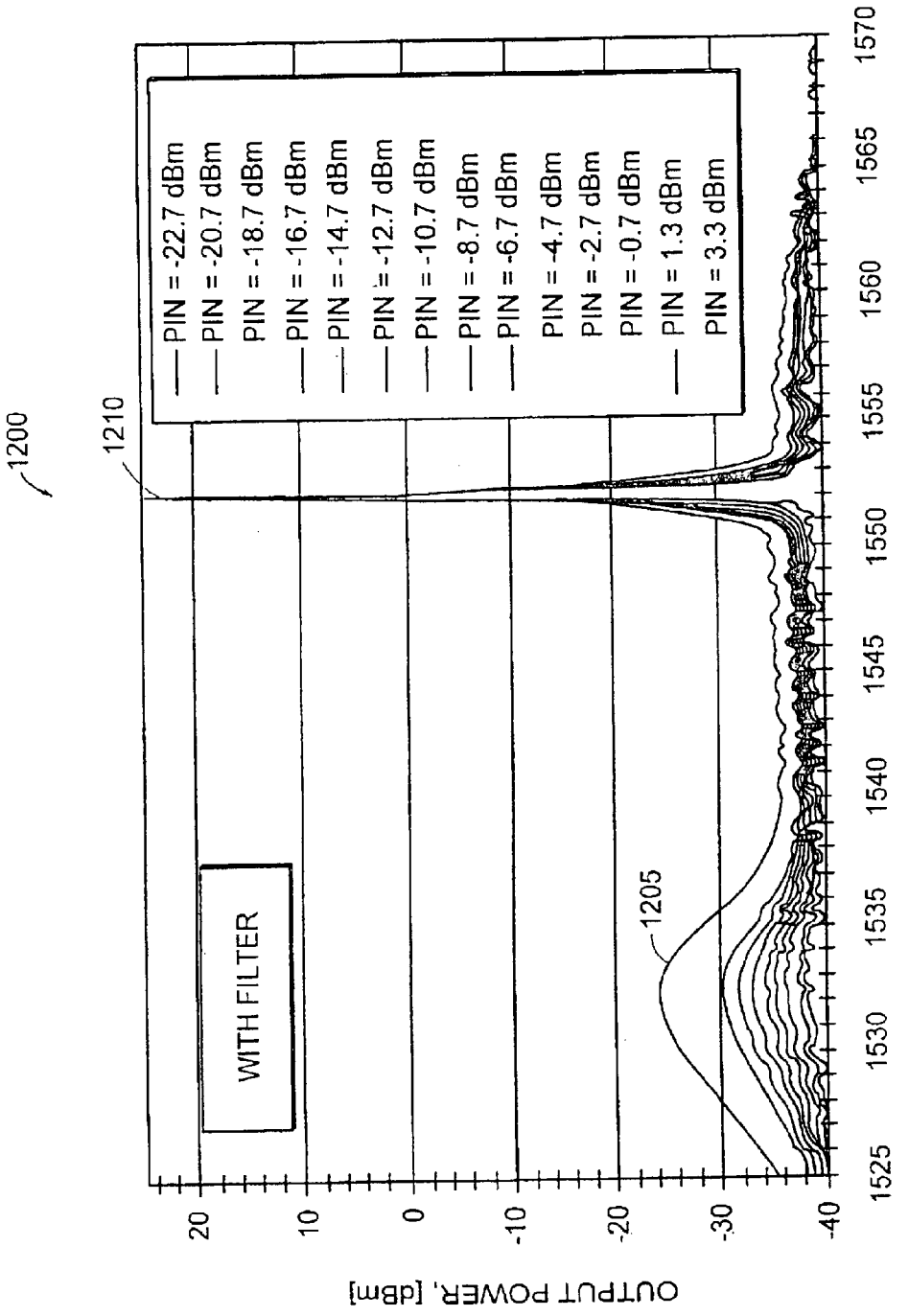

1200
1210
1205
WITH FILTER
PIN = -22.7 dBm
PIN = -20.7 dBm
PIN = -18.7 dBm
PIN = -16.7 dBm
PIN = -14.7 dBm
PIN = -12.7 dBm
PIN = -10.7 dBm
PIN = -8.7 dBm
PIN = -6.7 dBm
PIN = -4.7 dBm
PIN = -2.7 dBm
PIN = -0.7 dBm
PIN = 1.3 dBm
PIN = 3.3 dBm
OUTPUT POWER, [dBm]
20
10
0
-10
-20
-30
-40
1525
1530
1535
1540
1545
1550
1555
1560
1565
1570
WAVELENGTH, [nm]

FIG. 12

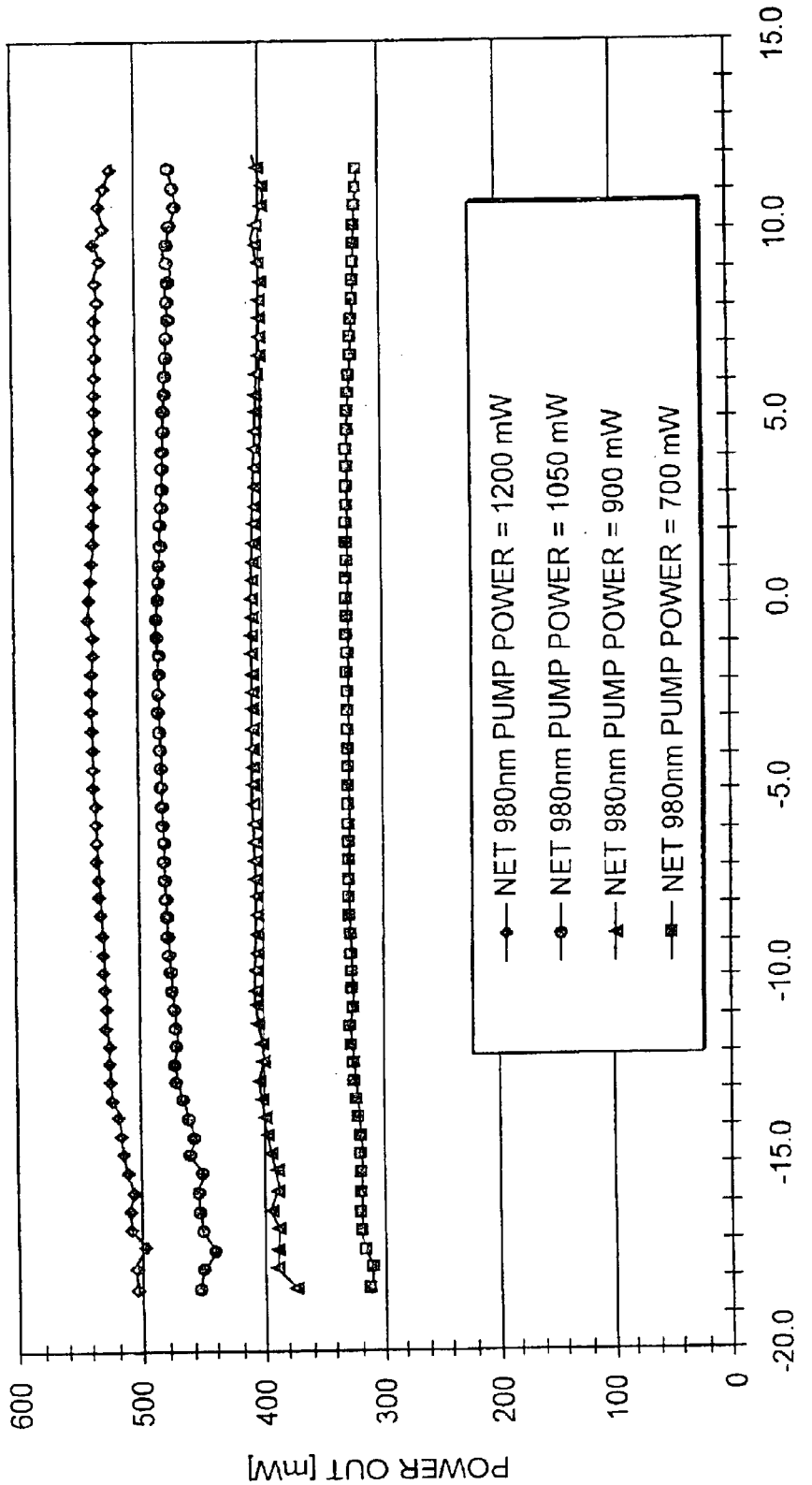

POWER OUT [mW]
600
500
400
300
200
100
0
-20.0
-15.0
-10.0
-5.0
0.0
5.0
10.0
15.0
POWER IN, [dBm]
NET 980nm PUMP POWER = 1200 mW
NET 980nm PUMP POWER = 1050 mW
NET 980nm PUMP POWER = 900 mW
NET 980nm PUMP POWER = 700 mW

FIG. 13

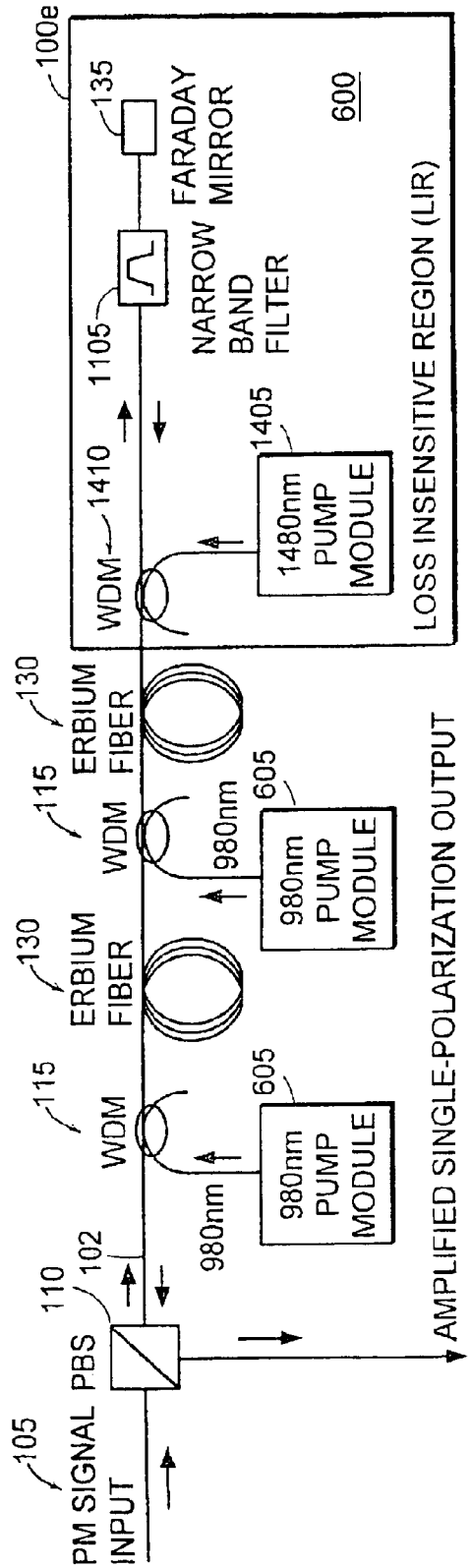

100e
135
FARADAY MIRROR
600
NARROW BAND FILTER
1105
1405
1480nm PUMP MODULE
WDM
1410
LOSS INSENSITIVE REGION (LIR)
130
ERBIUM FIBER
115
WDM
605
980nm
980nm PUMP MODULE
130
ERBIUM FIBER
115
WDM
605
980nm
980nm PUMP MODULE
102
110
PBS
105
PM SIGNAL INPUT
AMPLIFIED SINGLE-POLARIZATION OUTPUT

FIG. 14A

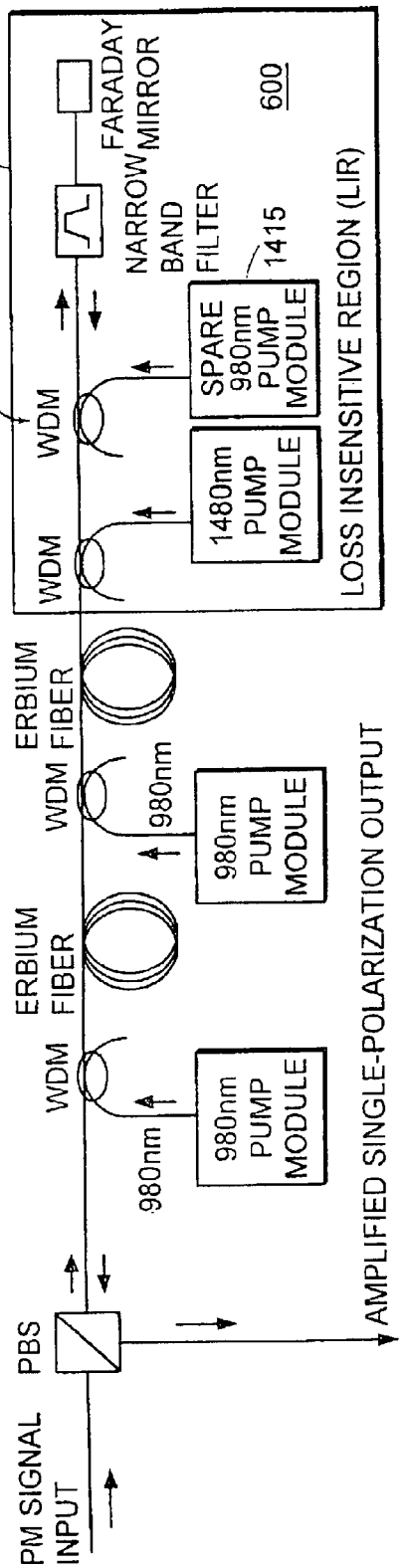


FIG. 14B

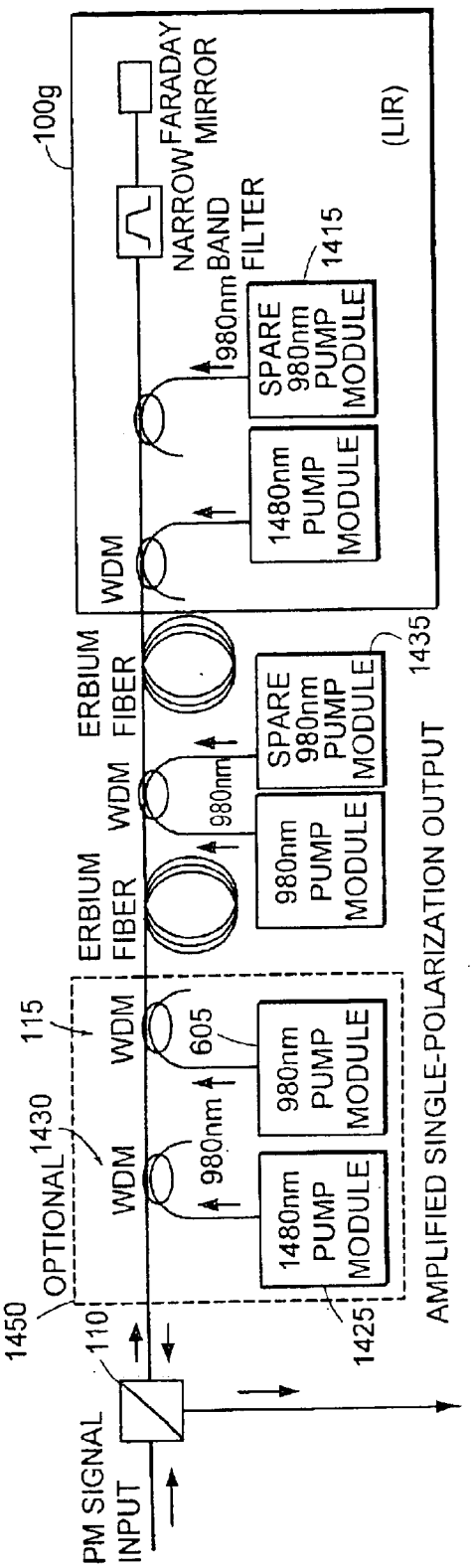


FIG. 14C

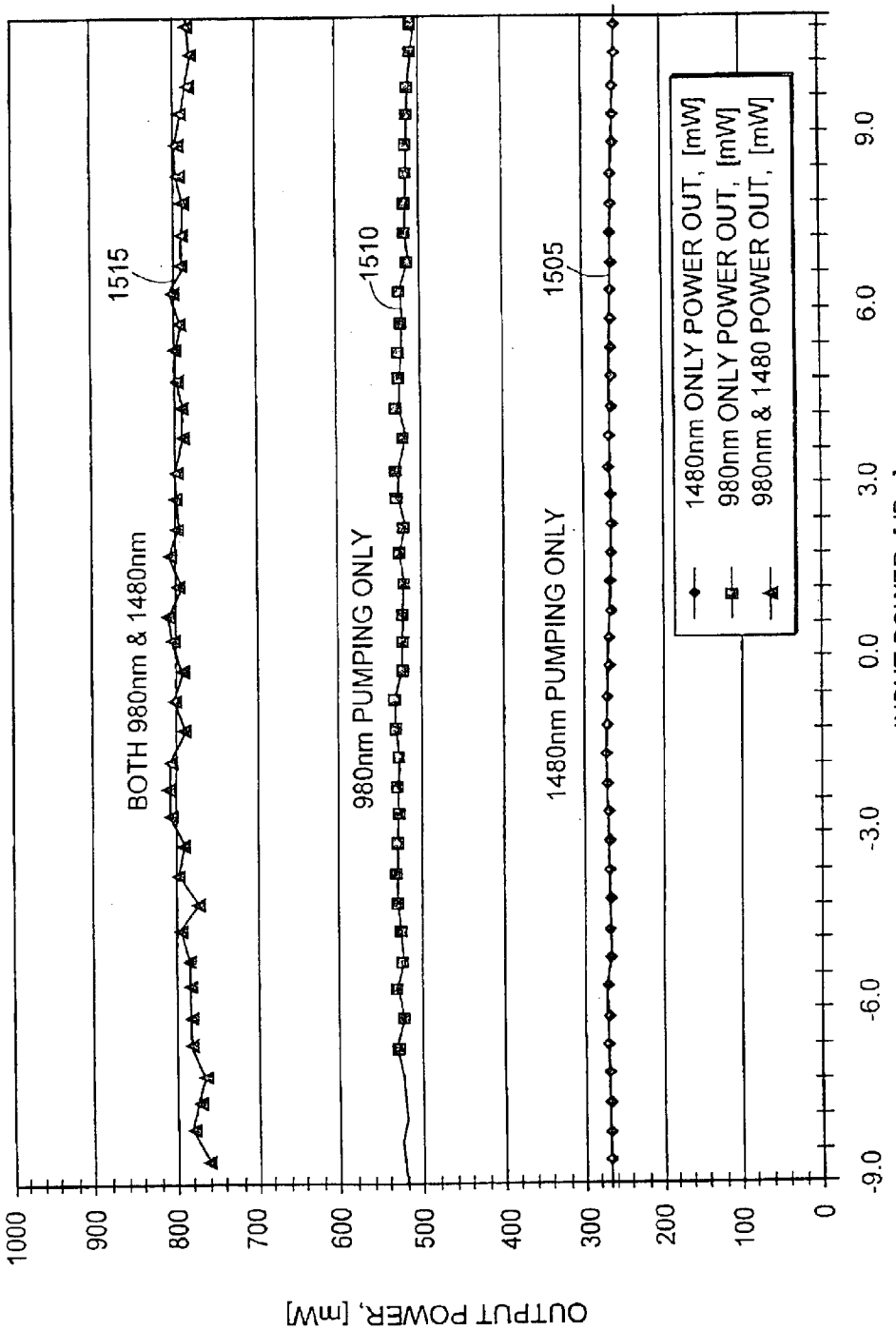

OUTPUT POWER, [mW]
1000
900
800
700
600
500
400
300
200
100
0
-9.0
-6.0
-3.0
0.0
3.0
6.0
9.0
INPUT POWER, [dBm]
1480nm ONLY POWER OUT, [mW]
980nm ONLY POWER OUT, [mW]
980nm & 1480 POWER OUT, [mW]
BOTH 980nm & 1480nm
980nm PUMPING ONLY
1480nm PUMPING ONLY
1515
1510
1505

FIG. 15

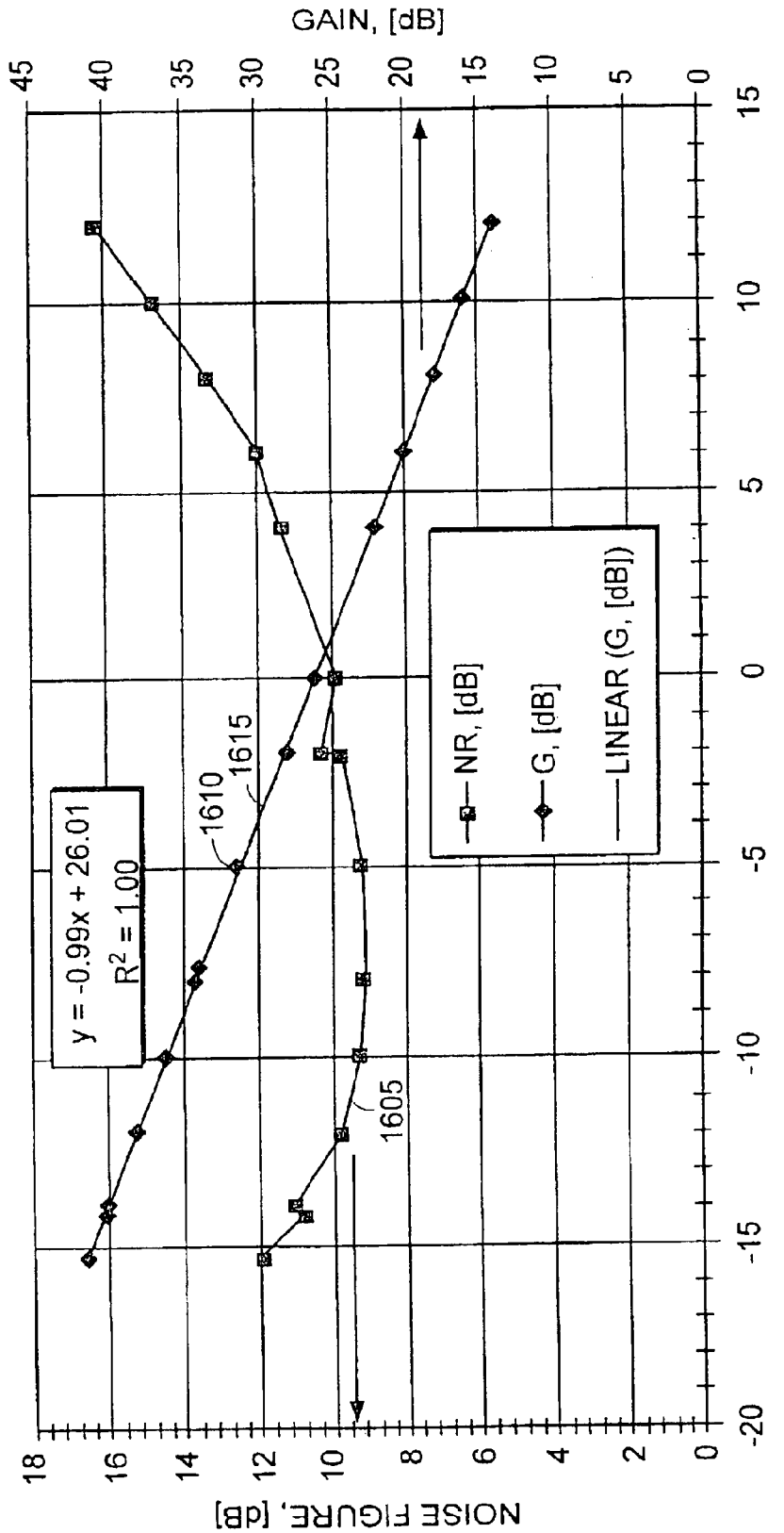

GAIN, [dB]
NOISE FIGURE, [dB]
POWER IN, [dBm]
NR, [dB]
G, [dB]
LINEAR (G, [dB])
y = -0.99x + 26.01
R2 = 1.00
1610
1615
1605

FIG. 16

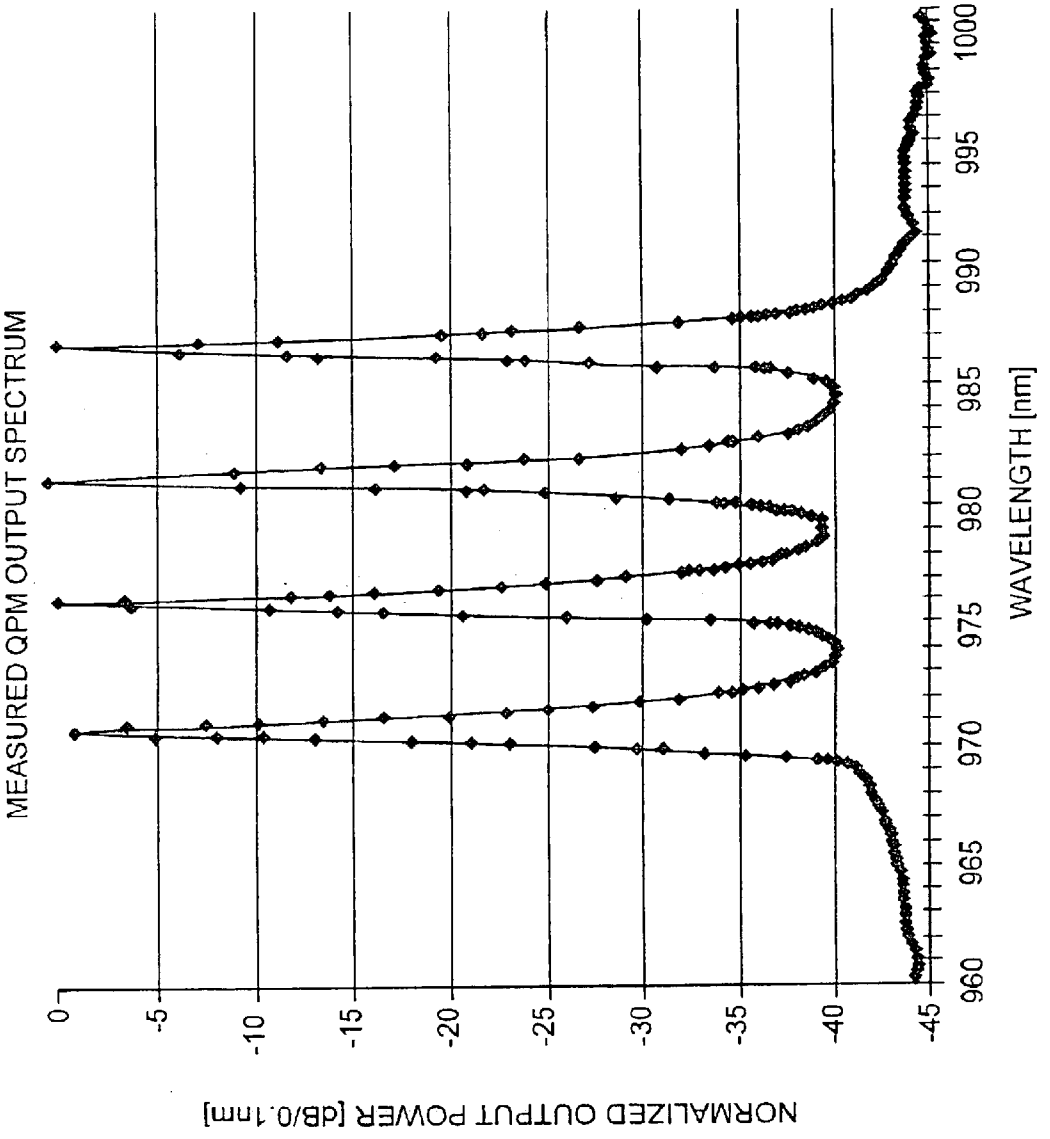

MEASURED QPM OUTPUT SPECTRUM
NORMALIZED OUTPUT POWER [dB/0.1nm]
0
-5
-10
-15
-20
-25
-30
-35
-40
-45
960
965
970
975
980
985
990
995
1000
WAVELENGTH [nm]

FIG. 17

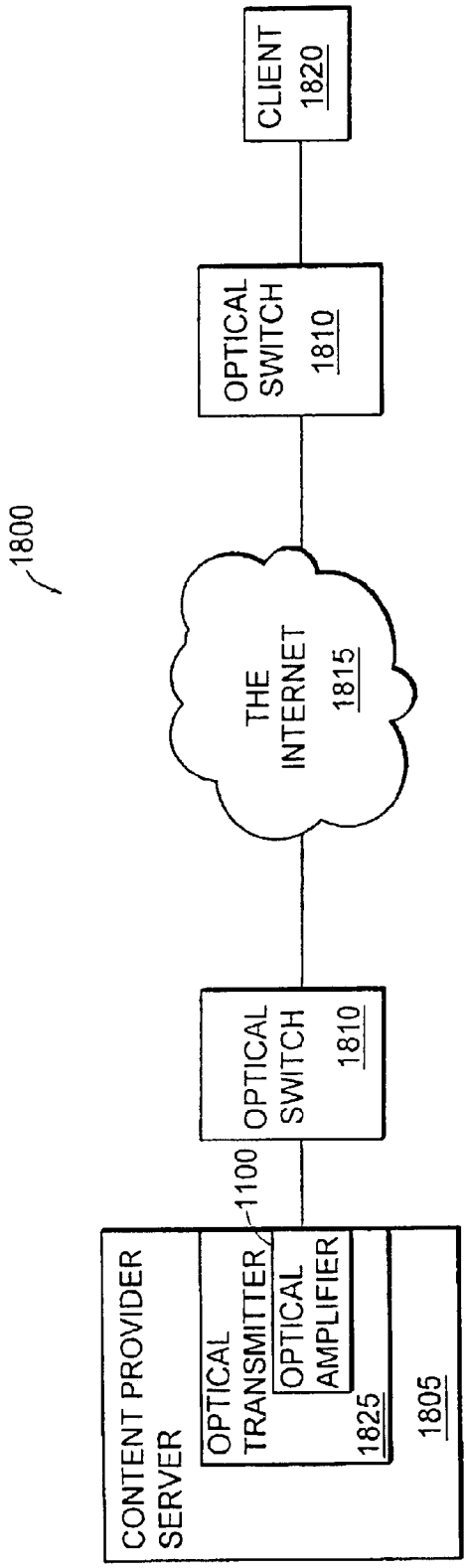

1800
CONTENT PROVIDER SERVER
1805
OPTICAL TRANSMITTER
1100
OPTICAL AMPLIFIER
1825
OPTICAL SWITCH
1810
THE INTERNET
1815
OPTICAL SWITCH
1810
CLIENT
1820

FIG. 18

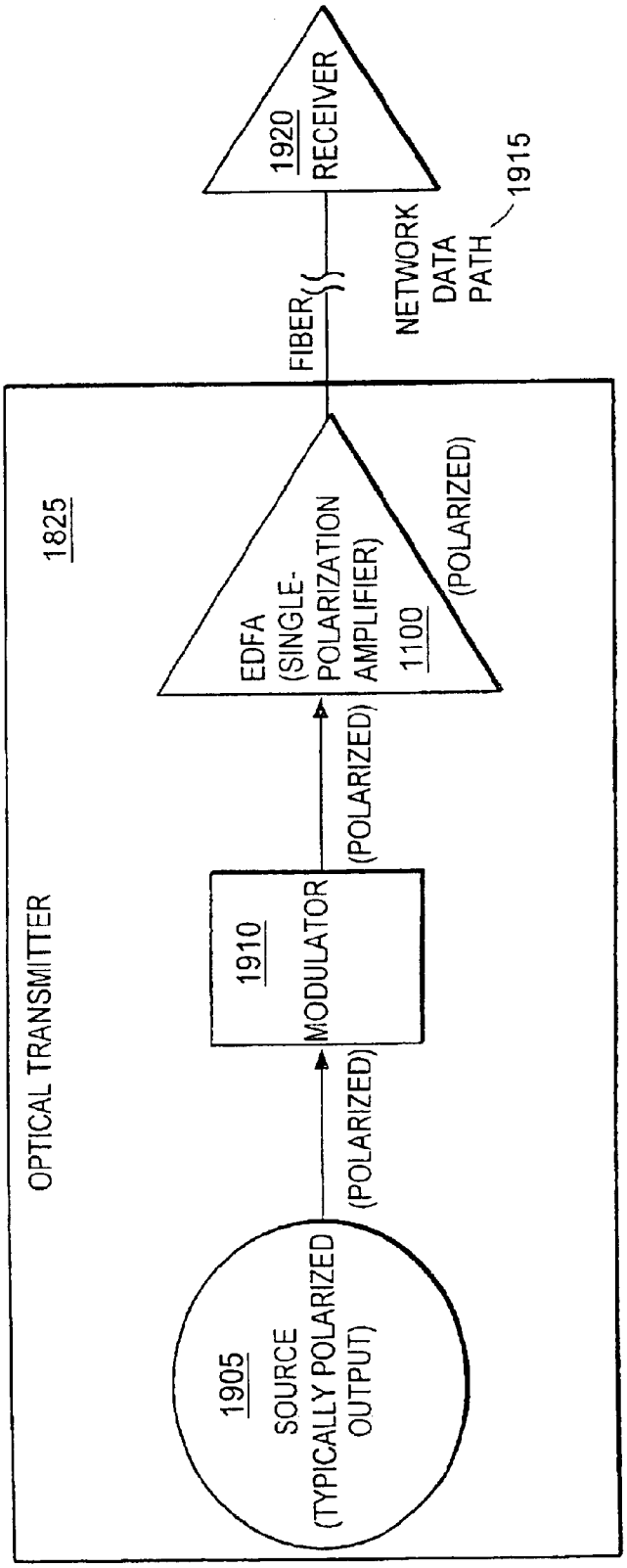

1920
RECEIVER
1915
NETWORK
DATA
PATH
FIBER
1825
EDFA
(SINGLE-
POLARIZATION
AMPLIFIER)
1100
(POLARIZED)
(POLARIZED)
1910
MODULATOR
(POLARIZED)
OPTICAL TRANSMITTER
1905
SOURCE
(TYPICALLY POLARIZED
OUTPUT)

FIG. 19

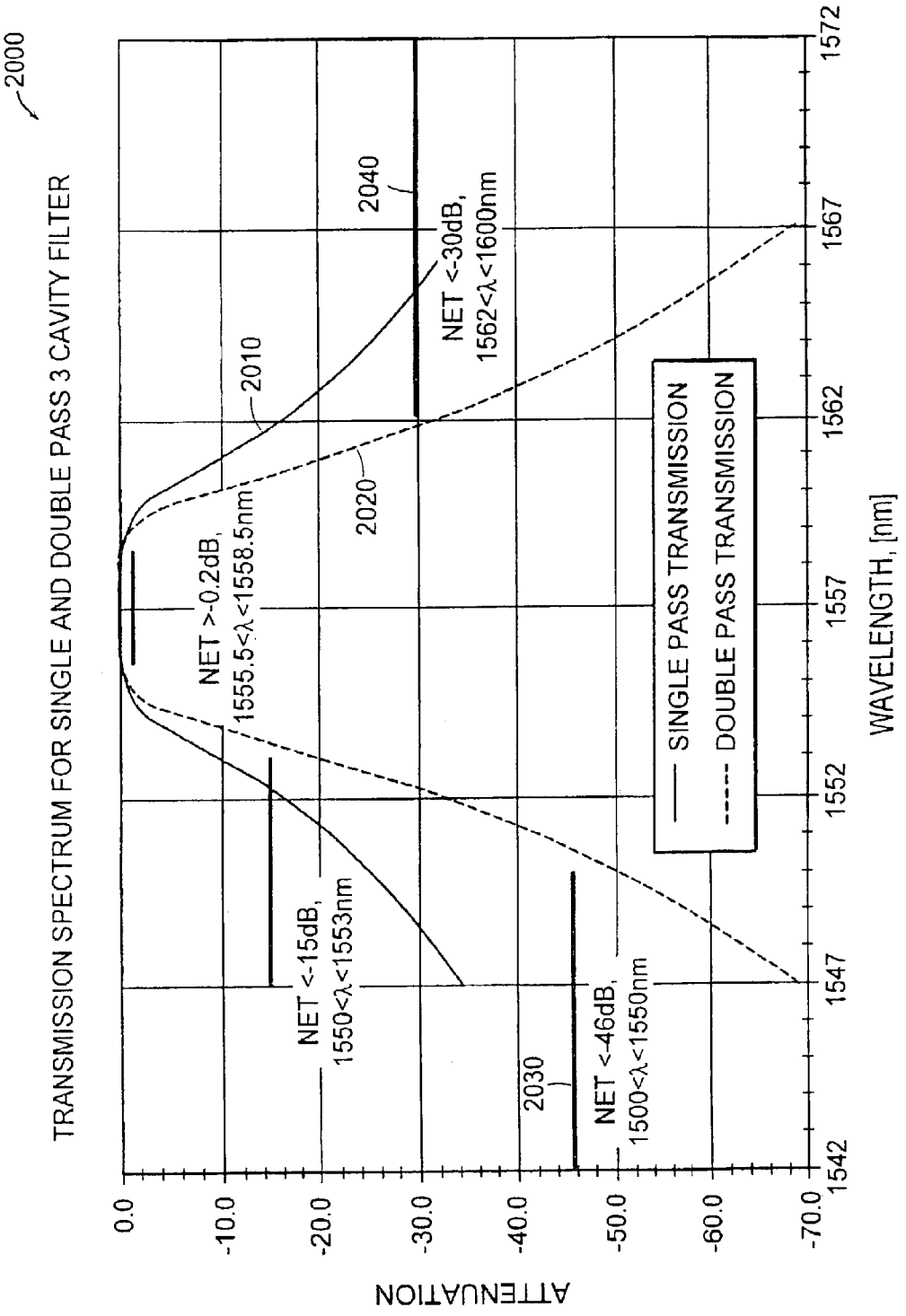

2000
TRANSMISSION SPECTRUM FOR SINGLE AND DOUBLE PASS 3 CAVITY FILTER
ATTENUATION
0.0
-10.0
-20.0
-30.0
-40.0
-50.0
-60.0
-70.0
1542
1547
1552
1557
1562
1567
1572
WAVELENGTH, [nm]
NET <-15dB, 1550<λ<1553nm
NET >-0.2dB, 1555.5<λ<1558.5nm
NET <-30dB, 1562<λ<1600nm
NET <-46dB, 1500<λ<1550nm
2010
2020
2030
2040
SINGLE PASS TRANSMISSION
DOUBLE PASS TRANSMISSION

FIG. 20

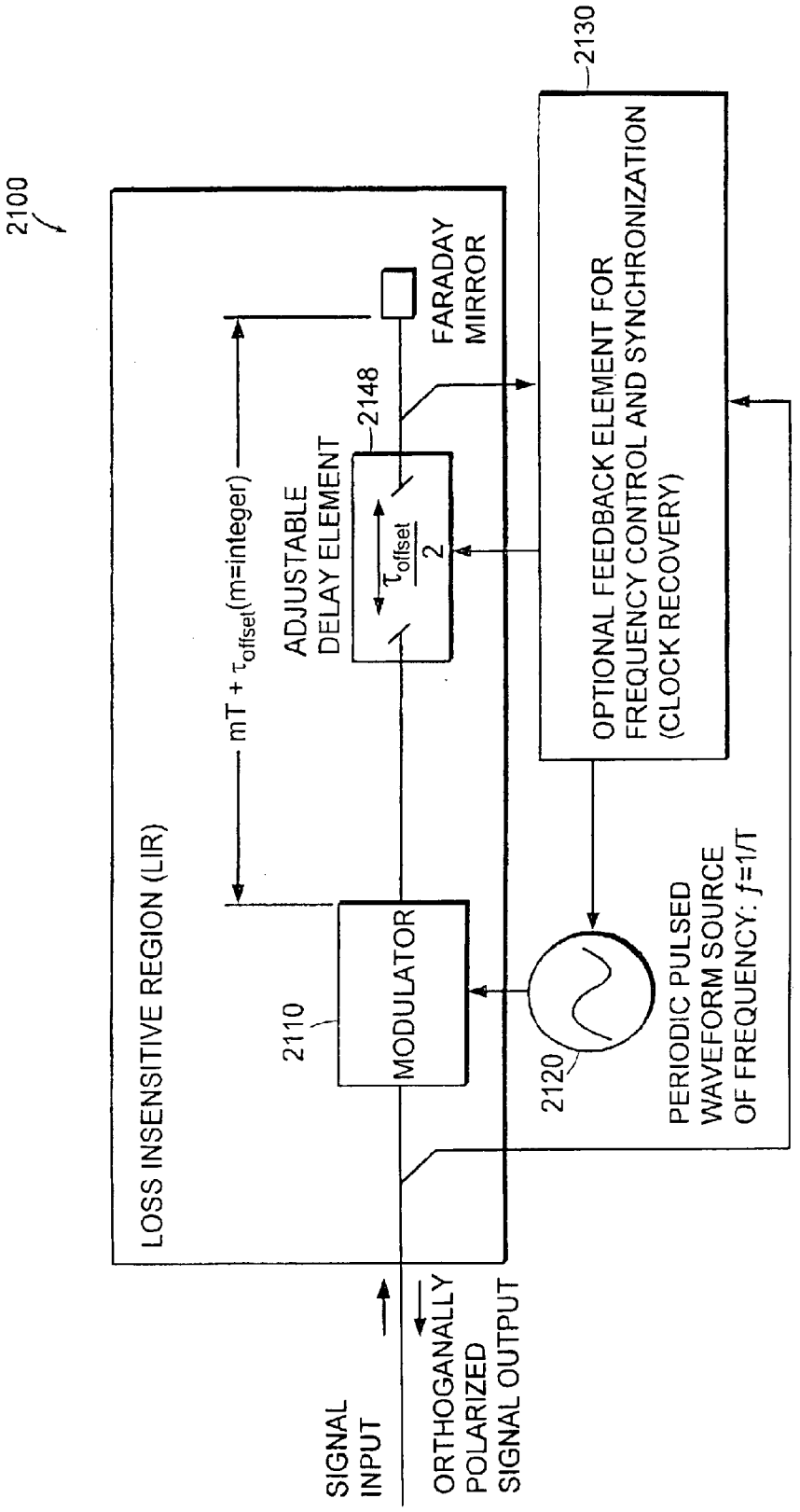

2100
LOSS INSENSITIVE REGION (LIR)
2130
OPTIONAL FEEDBACK ELEMENT FOR FREQUENCY CONTROL AND SYNCHRONIZATION (CLOCK RECOVERY)
FARADAY MIRROR
2148
ADJUSTABLE DELAY ELEMENT
$\tau_{offset}/2$
$mT + \tau_{offset}(m=integer)$
2110
MODULATOR
2120
PERIODIC PULSED WAVEFORM SOURCE OF FREQUENCY: $f=1/T$
SIGNAL INPUT
ORTHOGANALLY POLARIZED SIGNAL OUTPUT

FIG. 21

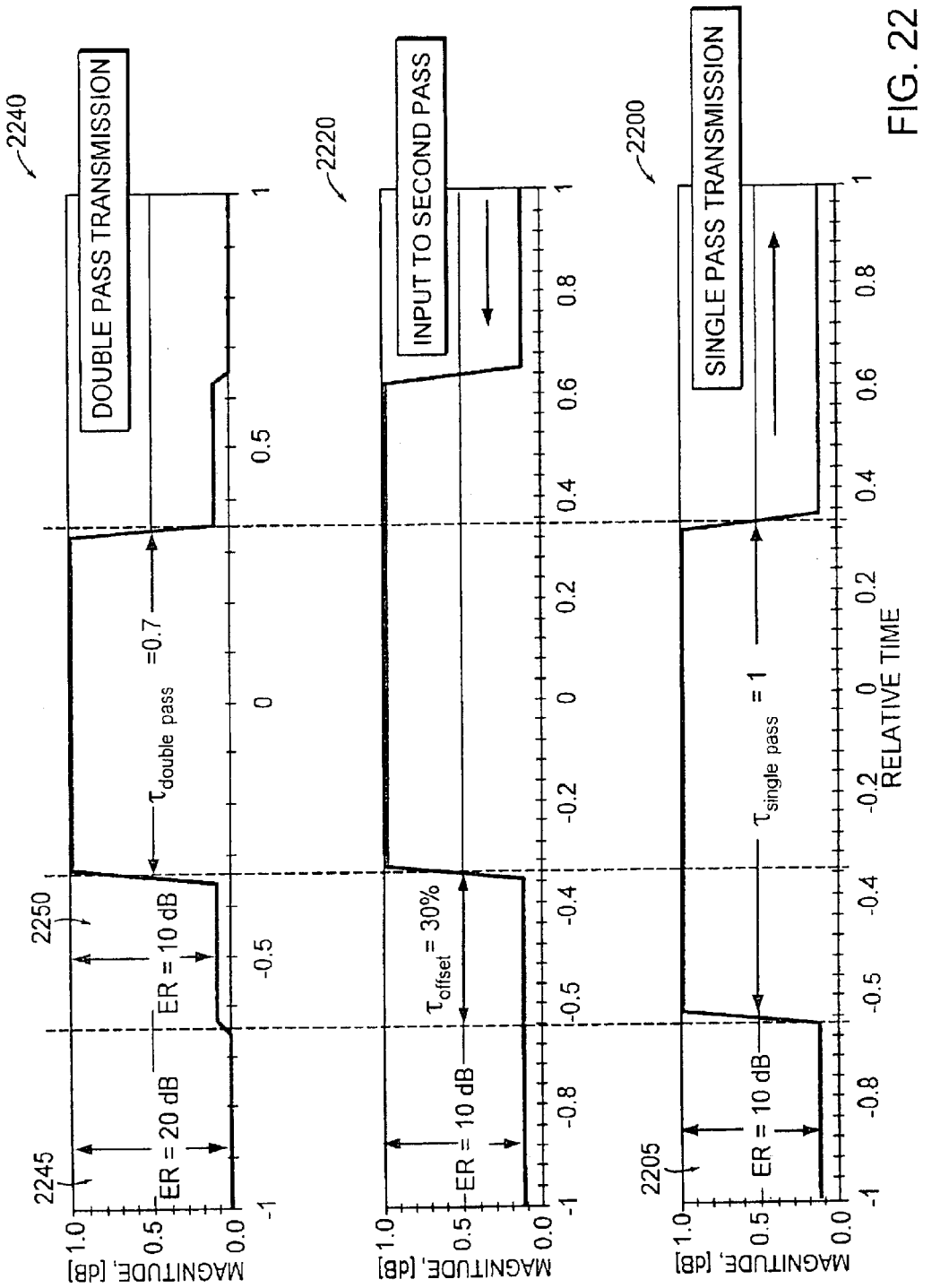

2240
DOUBLE PASS TRANSMISSION
2220
INPUT TO SECOND PASS
2200
SINGLE PASS TRANSMISSION
2250
2245
2205
ER = 10 dB
ER = 20 dB
ER = 10 dB
ER = 10 dB
$\tau_{double\ pass}$ =0.7
τ_{offset} = 30%
$\tau_{single\ pass}$ = 1
MAGNITUDE, [dB]
RELATIVE TIME

FIG. 22

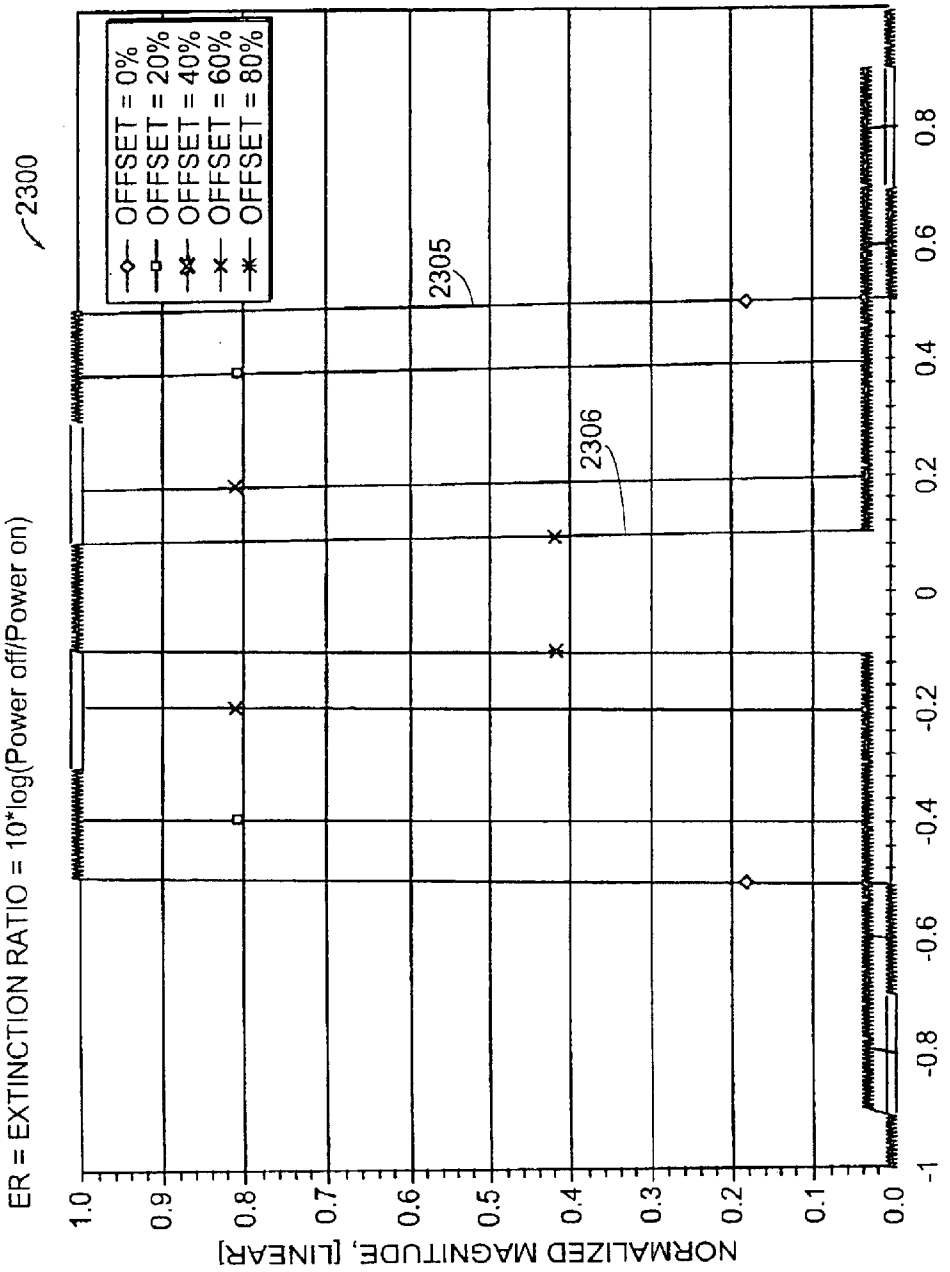

2300
ER = EXTINCTION RATIO = 10*log(Power off/Power on)
OFFSET = 0%
OFFSET = 20%
OFFSET = 40%
OFFSET = 60%
OFFSET = 80%
2305
2306
NORMALIZED MAGNITUDE, [LINEAR]
1.0
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0.0
-1
-0.8
-0.6
-0.4
-0.2
0
0.2
0.4
0.6
0.8
RELATIVE TIME

FIG. 23

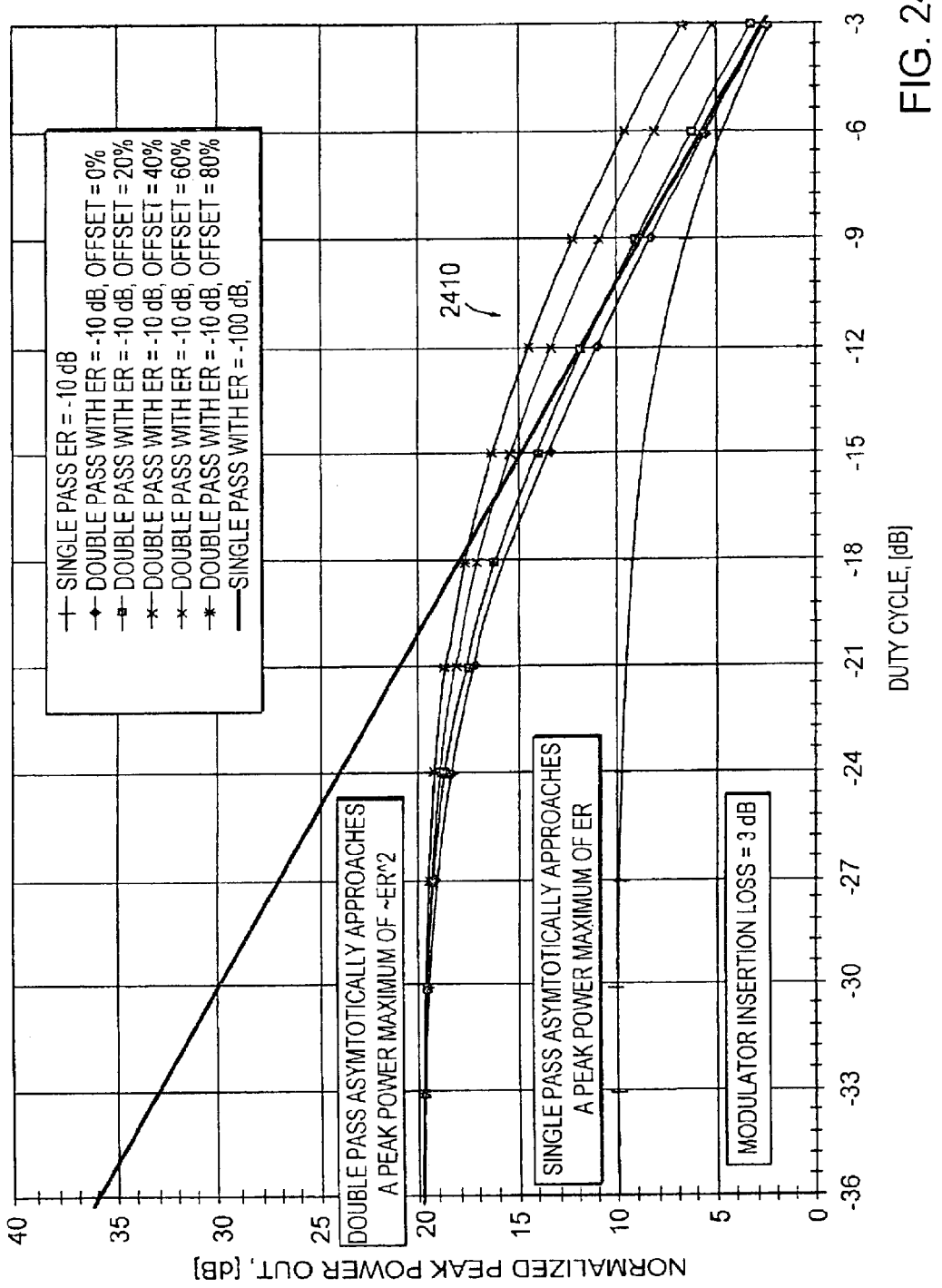

SINGLE PASS ER = -10 dB
DOUBLE PASS WITH ER = -10 dB, OFFSET = 0%
DOUBLE PASS WITH ER = -10 dB, OFFSET = 20%
DOUBLE PASS WITH ER = -10 dB, OFFSET = 40%
DOUBLE PASS WITH ER = -10 dB, OFFSET = 60%
DOUBLE PASS WITH ER = -10 dB, OFFSET = 80%
SINGLE PASS WITH ER = -100 dB,
2410
DOUBLE PASS ASYMTOTICALLY APPROACHES A PEAK POWER MAXIMUM OF ~ER^2
SINGLE PASS ASYMTOTICALLY APPROACHES A PEAK POWER MAXIMUM OF ER
MODULATOR INSERTION LOSS = 3 dB
NORMALIZED PEAK POWER OUT, [dB]
DUTY CYCLE, [dB]
40
35
30
25
20
15
10
5
0
-3
-6
-9
-12
-15
-18
-21
-24
-27
-30
-33
-36

FIG. 24

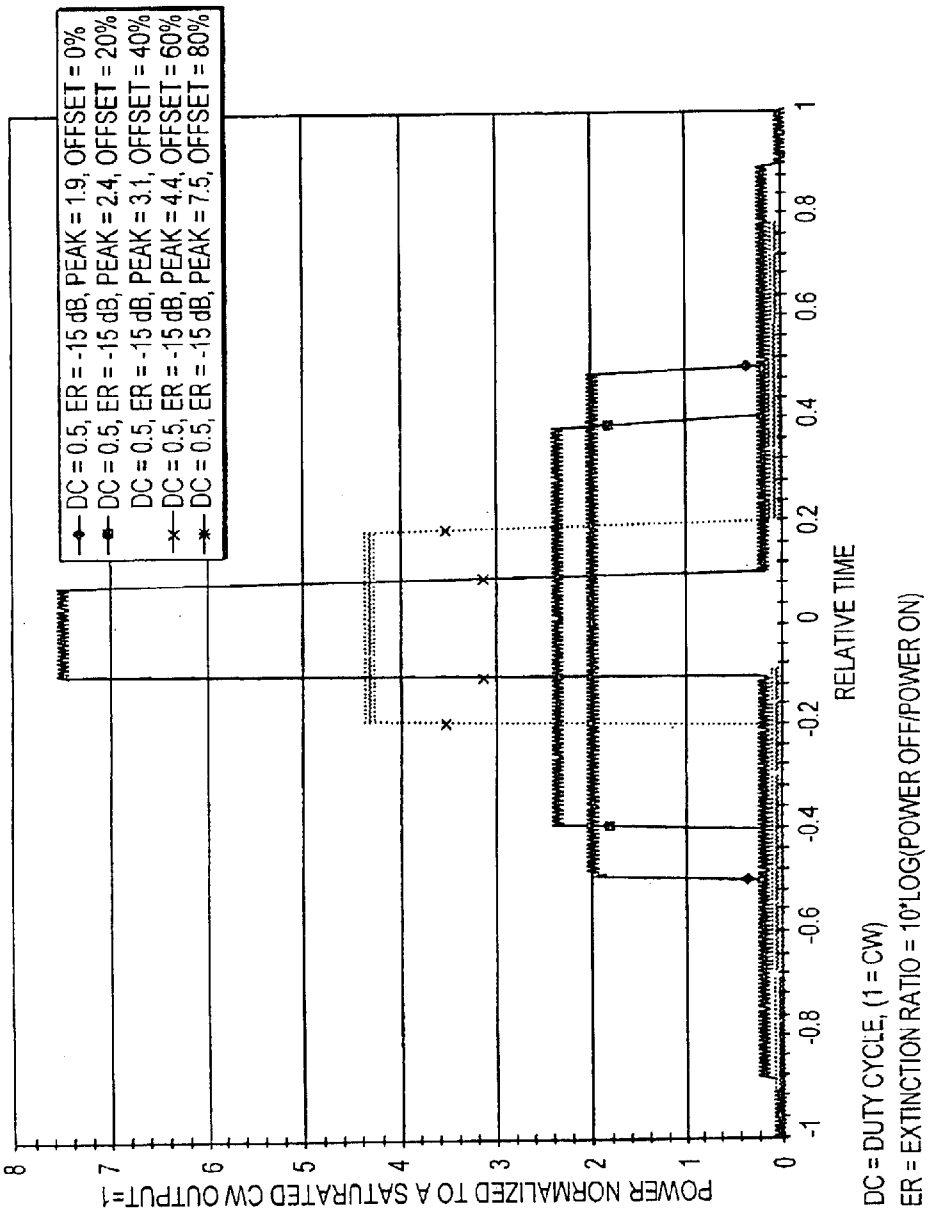

DC = 0.5, ER = -15 dB, PEAK = 1.9, OFFSET = 0%
DC = 0.5, ER = -15 dB, PEAK = 2.4, OFFSET = 20%
DC = 0.5, ER = -15 dB, PEAK = 3.1, OFFSET = 40%
DC = 0.5, ER = -15 dB, PEAK = 4.4, OFFSET = 60%
DC = 0.5, ER = -15 dB, PEAK = 7.5, OFFSET = 80%
POWER NORMALIZED TO A SATURATED CW OUTPUT=1
RELATIVE TIME
DC = DUTY CYCLE, (1 = CW)
ER = EXTINCTION RATIO = 10*LOG(POWER OFF/POWER ON)

FIG. 25

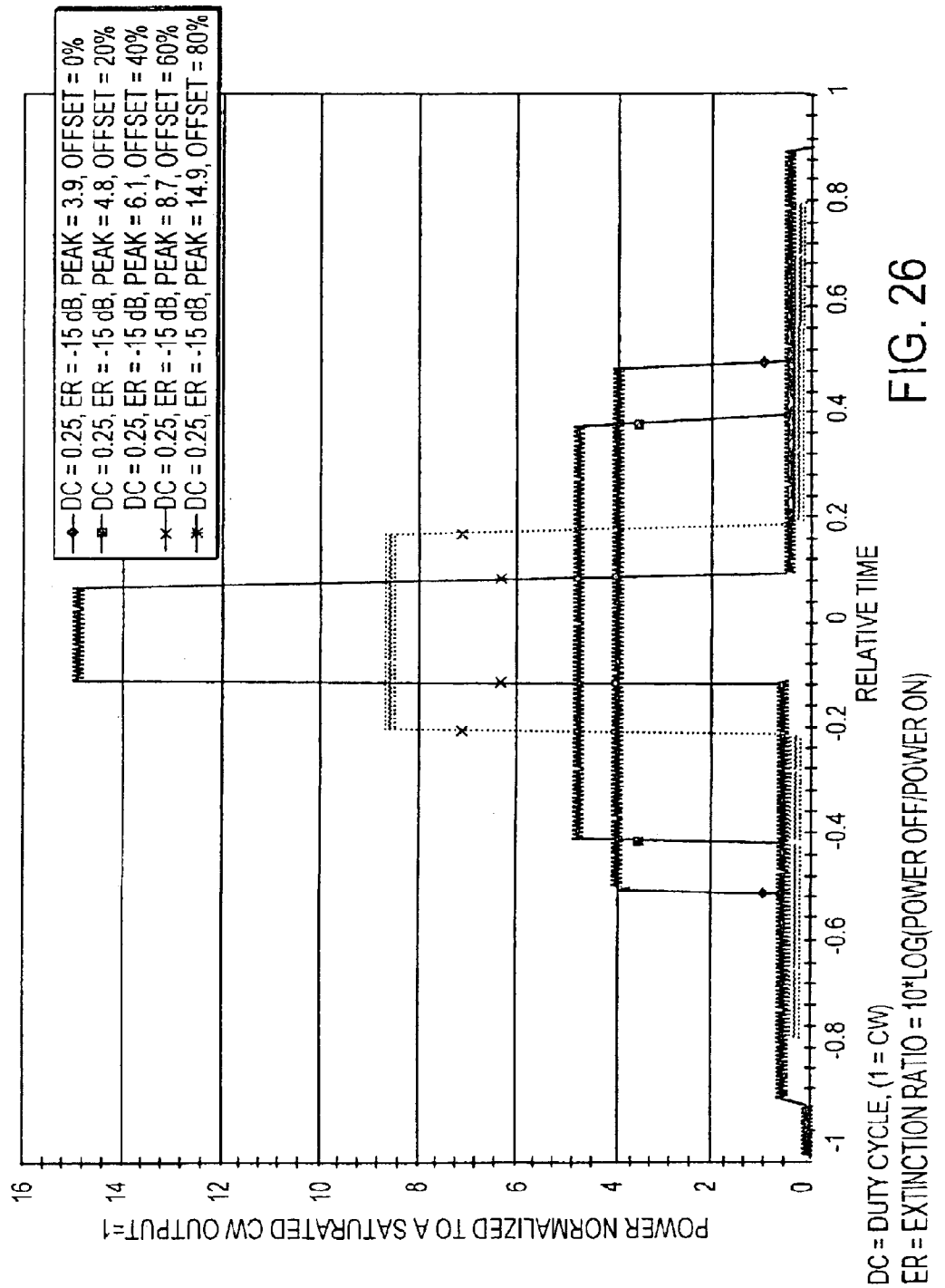

DC = 0.25, ER = -15 dB, PEAK = 3.9, OFFSET = 0%
DC = 0.25, ER = -15 dB, PEAK = 4.8, OFFSET = 20%
DC = 0.25, ER = -15 dB, PEAK = 6.1, OFFSET = 40%
DC = 0.25, ER = -15 dB, PEAK = 8.7, OFFSET = 60%
DC = 0.25, ER = -15 dB, PEAK = 14.9, OFFSET = 80%
POWER NORMALIZED TO A SATURATED CW OUTPUT=1
RELATIVE TIME
DC = DUTY CYCLE, (1 = CW)
ER = EXTINCTION RATIO = 10*LOG(POWER OFF/POWER ON)

FIG. 26

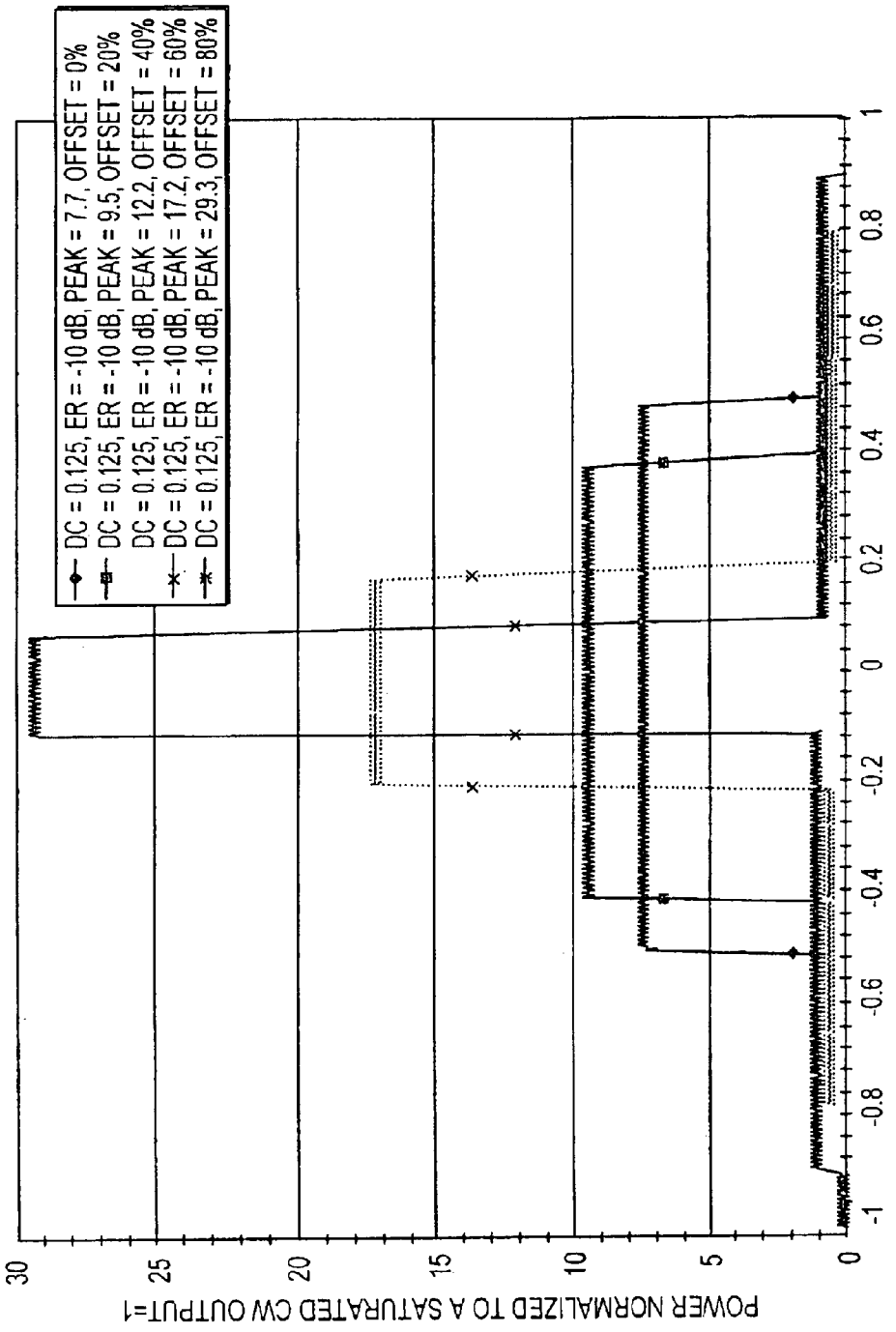

DC = 0.125, ER = -10 dB, PEAK = 7.7, OFFSET = 0%
DC = 0.125, ER = -10 dB, PEAK = 9.5, OFFSET = 20%
DC = 0.125, ER = -10 dB, PEAK = 12.2, OFFSET = 40%
DC = 0.125, ER = -10 dB, PEAK = 17.2, OFFSET = 60%
DC = 0.125, ER = -10 dB, PEAK = 29.3, OFFSET = 80%
POWER NORMALIZED TO A SATURATED CW OUTPUT=1
30
25
20
15
10
5
0
-1
-0.8
-0.6
-0.4
-0.2
0
0.2
0.4
0.6
0.8
1
RELATIVE TIME
DC = DUTY CYCLE, (1 = CW)
ER = EXTINCTION RATIO = 10*LOG(POWER OFF/POWER ON)

FIG. 27

METHOD AND APPARATUS FOR STABILIZING A HIGH-GAIN, HIGH-POWER SINGLE POLARIZATION EDFA

GOVERNMENT SUPPORT

The invention was supported, in whole or in part, by a grant F19628-95-C-0002 from United States Air Force. The Government has certain rights in the invention.

BACKGROUND OF THE INVENTION

Free-space optical transmitters are typically required to provide a high-power, single-polarization output. An optical amplifier capable of providing a high-power, single-polarization output is presented in a paper, Hakimi et al., "High-power Single-polarization EDFA with Wavelength Multiplexed pumps", CLEO '98, CWK1, 1998.

High-power optical amplifiers, such as erbium-doped fiber amplifiers (EDFA's), are often employed in free-space communications. Single-polarization EDFA's provide additional capabilities for polarization diplexing and improved communication performance, since orthogonally polarized amplified spontaneous emission (ASE) can be eliminated at both receiver and transmitter. Such features can offer substantial benefit in free-space links, where an improvement in single-polarization receiver sensitivity directly reduces required transmitter power.

High gain enables a power amplifier to output its maximum saturated output power over an extended range of input power levels. In master oscillator power amplifier (MOPA) designs, this feature makes the transmitter less sensitive to insertion loss changes in the elements leading up to the power amplifier. Furthermore, saturated EDFA's are average power limited (APL), and, therefore, peak output power is inversely proportional to the duty-cycle of the input.

FIG. **1** is a schematic diagram of the erbium-doped fiber amplifier (EDFA) **100***a* by Hakimi et al., which is a two-stage, double-pass, polarization-maintaining EDFA with a high-power, saturated output composed of reliable, commercially available components. FIGS. **2–5** further illustrate the EDFA of FIG. **1**.

Referring now to FIG. **1**, a 1550 nm input optical signal **105** is coupled to a standard, single-mode, optical fiber **110** via a polarization beam splitter (PBS) **107**. The input signal **105** travels in a forward pass through the optical fiber **110**, among other optical media. The EDFA **100***a* of FIG. **1** achieves a high output power level by multiplexing four pump lasers **125** together with polarization-insensitive, dense, WDM, fused tapered couplers **120**. See M. N. McLandrich et al., J. Lightwave Technol. 9, 442–447 (1991). The pump diode laser wavelengths range from 970 nm to 985 nm, with 5 nm of separation between each. According to Hakimi et al., at the recommended operating current, the nominal power of each pump before the WDM combiner is 90 mW, and the output pump power from each set of four combined pump lasers is 330 mW. The output from the dense WDM **120** is coupled to the optical medium, carrying the input signal **105**, by a standard WDM **115**.

In the forward pass, the output from the WDM **115** (i.e., the input signal **105** and signals from the diode pumps **125**) encounters an erbium-doped fiber **130**. The 970 nm–985 nm outputs from the four diode pumps **125** get absorbed by the erbium-doped fiber **130**, increasing the energy level in the erbium-doped fiber **130**. Unlike the 970 nm–985 nm outputs from the diode pumps **125**, the 1550 nm input signal **105** passes through the erbium-doped fiber **130**, increasing in power as a result of encountering the erbium-doped fiber **130** charged by the four diode pumps **125**. Because the input signal **105** is amplified by the erbium-doped fiber **130**, the erbium-doped fiber **130** is often referred to as an optical gain medium.

FIG. **2** is a schematic diagram representing how the erbium-doped fiber **130**, in combination with the output energy from the four diode pumps **125**, provides gain to amplify the input signal **105**. As stated above, the pump energy **205** is absorbed by the erbium-doped fiber **130**. The energy absorption representation **210** indicates that the energy in the erbium-doped fiber **130** reaches a peak level, Emax. The energy relaxes from its maximum potential energy level to a nominal potential energy level, Enom, as indicated by an energy relaxation representation **215**. In this manner, pump energy is used to transfer energy from the ground state, Emin, to the excited state Enom, creating an energy inversion. Enom corresponds to the energy of the input signal wavelength. Then, when the input signal **105** encounters the excited-state erbium-doped fiber **130**, stimulated emission occurs, as indicated by a stimulated emission representation **220**.

As a result of the release of optical energy resulting from the stimulated emission process, a signal photon **225** of 1.5 μm wavelength entering the energy-enhanced erbium-doped fiber **130** exits as multiple photons **230** of the same wavelength, thus amplifying the signal.

Referring again to FIG. **1**, a second WDM **115** and erbium-doped fiber **130** are encountered by the input signal having been once amplified. Following the second erbium-doped fiber **130**, the twice amplified input signal encounters a Faraday mirror **135**, causing the twice amplified input signal to travel in a reverse pass with a 90 degree polarization rotation. The signal traveling in the reverse pass is amplified a third and a fourth time, as it traverses through the optical gain mediums **115** to the polarization beam splitter **107**. The output **140***a* is the saturated output from the EDFA **100***a*.

The input port of the EDFA **100***a*, consisting of the fiber-pigtailed polarization beam splitter **110**, has a 0.4-dB port-to-port loss. The Er-fiber (i.e., erbium-doped fiber) splice losses, Faraday mirror loss, and 980/1550 WDM losses are 0.1 dB, 0.33 dB, and 0.1 dB, respectively. Each amplifier stage uses approximately 15 meters of conventional erbium-doped fiber.

FIG. **3** shows the output power verses the input signal power for the EDFA **100***a* measured after the polarization beam splitter **107**. The curve defined by the triangles is a result of the energy pumps providing 330 mW/stage (triangles). In this case, the output power of the EDFA **100***a* is just over 255 mW at 1556 nm, which is near the peak of the gain. When the pump lasers are turned up above the recommended operating point to 400 mW/stage (diamonds), the saturated output power is 315 mW.

FIG. **4** illustrates the wavelength dependence of the output of the EDFA **100***a*. A 1 mW input signal and 330 mW/stage pump power are held constant in generating the response curve. The output power is above 240 mW over a 30 nm range.

FIG. **5A** is a transfer function **500** of a typical amplifier, of which the EDFA **100***a* is a member. The transfer function has two regions: a small signal gain region **505** and a saturated output gain region **510**. The gain curve **515** in the small signal gain region **505** increases at a typical rate, where Pout equals g_o*Pin, and g_o is the small signal gain. Note that, in dB, the linear expression Pout=g_o*Pin trans-

forms to Pout [dB]=(g_o+Pin) [dB]. In the saturated output gain region **510**, the curve **515** asymptotically increases to Psat_out. The EDFA **100***a* of FIG. **1** operates entirely in the saturated output gain region **510** for input power levels about −15 dBm. However, for input power levels of below −15 dBm, the EDFA **100***a* becomes unstable, oscillating instead of outputting a constant power level for an input signal of constant power level. The EDFA **100***a* does not simply revert to a small signal gain amplifier, as might be suggested by the transfer function, because the EDFA **100***a* is designed only to operate stably for input power levels that drive the amplifier far into the saturated output gain region.

FIG. **5**B is a transfer function of gain versus output power corresponding to the transfer function of FIG. **5**A.

SUMMARY OF THE INVENTION

A fault-tolerant, loss-insensitive region in a two-stage, double-pass, polarization maintaining (PM) EDFA has been identified, in which assertion of optical elements can be used for, among other reasons, to improve stability, output power, and efficiency of the EDFA. Employing the principles of the present invention, stable, greater than 0.5 Watt output power levels are obtainable for input power levels to the EDFA spanning over a 30 dB dynamic range, and 980/1550 nm conversion efficiencies that can exceed 42%.

In one embodiment of the present invention, an optical amplifier includes an amplifying optical path of elements of low insertion losses, including a non-lasing optical gain medium through which an optical signal is amplified. The optical amplifier further includes an optical return path by which amplified light from a first pass returns through the gain medium in a reverse pass through the gain medium. At least one optical element optically disposed in the optical return path, between the forward pass and the reverse pass, has a loss substantially greater than the insertion losses of the non-gain elements within the amplifying optical path. The amplifying optical path is sometimes referred to as the loss-sensitive region, and the region beyond the amplifying optical path (i.e., between the forward pass and reverse pass) is sometimes referred to as the loss-insensitive region (see FIG. **6**, **600**). Non-gain optical elements may include, for example, optical coupling elements (e.g., polarization beam splitters, circulators, or wavelength multiplexers) and splices.

The elements in the amplifying optical path are typically selected to have insertion losses less than about 0.5 dB, preferably less than about 0.2 dB. The optical element(s) between the forward pass and the reverse pass can have insertion loss(es) of greater than 0.5 dB without significant effect on the output power of the optical amplifier.

The optical return element, used to direct the input signal into the optical amplifier and direct the amplified signal out of the optical amplifier, is typically a beam splitter, polarizing beam splitter, or circulator.

In the preferred embodiment, each gain medium includes at least one erbium-doped fiber. To increase the available energy in the gain medium, the amplifier includes at least one energy pump coupled to the gain medium. For an erbium-doped fiber, the energy pump is typically chosen to output a 980 nm wavelength signal. For the 980 nm pumps wavelengths composed of about 500 mW of wavelength multiplex pump power, pumping a Lucent® HP980 erbium fiber, the erbium-doped fiber is preferably between about 15 and 17 meters in length. The length of the fiber is dependent on type of fiber and pump power levels.

The optical element(s) in the loss-insensitive region include(s) at least one of the following elements: a band pass filter, band reject filter, notch filter, comb filter, beam shaper, at least one wavelength division multiplexer coupling at least one 1480 nm wavelength output signal to a respective gain medium or at least one 980 nm WDM or pump element coupling that can be used for reverse pumping or redirecting excess forward pump energy, such as a cladding pump. Further, the optical return element is selected from a group consisting essentially of: a mirror, Faraday mirror, polarization rotation reflection element, beam splitter and plural mirrors, or continuous optical medium loop. In contrast to a laser, in the EDFA, the round-trip gain of the optical signal is less than the round-trip loss of the optical signal. In other words, the EDFA amplifies the input signal, and it is desirable to minimize frequencies at which lasing might occur.

In one implementation, the amplifying optical path of elements includes an input element, first WDM and second WDM in the loss-sensitive region, third WDM in the loss-insensitive region, at least one optical filter also in the loss-insensitive region, and optical return element. In this implementation, the input element is a polarizing beam splitter that directs the input signal into the optical medium of the amplifier and out of the optical medium of the amplifier after a double-pass through two optical gain mediums. The first WDM inserts into the first non-lasing optical gain medium a 980 nm signal from at least one energy pump. The second WDM inserts a 980 nm signal from at least one energy pump into the second non-lasing optical gain medium. The third WDM inserts into the first and second optical gain media a 1480 nm signal from at least one energy pump. The optical filter in the loss-insensitive region (i) has an insertion loss that can be substantially greater than the insertion losses of optical elements external from the loss-insensitive region and (ii) passes essentially the optical signal. In this implementation, the optical return element is preferably a Faraday mirror. The optical signal that has been amplified by the optical amplifier of this embodiment is substantially singularly polarized through use of the polarizing beam splitter and Faraday mirror. This implementation allows for multiple spare energy pumps in both the loss-sensitive and loss-insensitive regions and at both 980 nm and 1480 nm wavelengths.

In one embodiment, at least one of the optical elements in the optical return path between the forward pass and the reverse pass restricts the optical signal to wavelengths of interest to prevent other wavelengths from lasing, thereby increasing stability. The optical amplifier is suitable for use in free-space and fiber optic network applications.

BRIEF DESCRIPTION OF THE DRAWINGS

The foregoing and other objects, features and advantages of the invention will be apparent from the following more particular description of preferred embodiments of the invention, as illustrated in the accompanying drawings in which like reference characters refer to the same parts throughout the different views. The drawings are not necessarily to scale, emphasis instead being placed upon illustrating the principles of the invention.

FIG. **1** is a schematic diagram of a prior art two-stage, erbium-doped fiber amplifier (EDFA) with a linear, polarization-maintaining output;

FIG. **2** is a schematic diagram depicting energy absorption in an erbium-doped fiber employed in the prior art amplifier of FIG. **1**;

FIG. **3** is a measured plot of the output power versus input power for the prior art amplifier of FIG. **1**;

FIG. **4** is a plot of the output power versus wavelength for the prior art amplifier of FIG. **1**;

FIG. **5**A is a plot of the output power versus the input power for a generic amplifier having an indication of the saturation level for the prior art amplifier of FIG. **1**;

FIG. **5**B is a plot of amplifier gain versus output power corresponding to the plot of FIG. **5**A;

FIG. **6** is a schematic diagram of an optical amplifier having a loss-insensitive region according to the principles of the present invention;

FIG. **7**A is a plot of amplified signal power versus fiber length related to the erbium-doped fiber employed in the optical amplifier of FIG. **6**;

FIG. **7**B is a simulated plot of output power versus reflection loss (or attenuation) within the loss-insensitive region for a two-stage double-pass EDFA with Faraday rotator mirror shown in FIG. **6**;

FIG. **8** is a plot of signal power gain versus fiber lengths of the optical amplifier of FIG. **6**;

FIG. **9**A is a schematic diagram of the optical amplifier of FIG. **6** employing a variable attenuator in the loss-insensitive region;

FIG. **9**B is a plot of output power of the optical amplifier versus additional attenuation introduced by the variable attenuator of FIG. **9**A;

FIG. **10**A is a plot of output power versus wavelength for the prior art optical amplifier of FIG. **1**;

FIG. **10**B is a plot showing high peak power, self pulsing that can occur in high-gain, high-power, optical amplifiers.

FIG. **11**A is an embodiment of the optical amplifier of FIG. **6** employing a narrow-band filter in the loss-insensitive region;

FIG. **11**B is a plot of output power versus input power transfer function curves for the optical amplifiers of FIGS. **1** and **11**A;

FIG. **12** is a plot of the output power versus wavelength similar to FIG. **10**A but for the present invention optical amplifier of FIG. **11**A;

FIG. **13** is a set of plots of output power versus input power for the optical amplifier of FIG. **11**A;

FIGS. **14**A–**14**C are block diagrams of various embodiments of the optical amplifier of FIG. **11**A also including at least one WDM in the loss-insensitive region and spare energy pumps in the loss-sensitive and loss-insensitive regions;

FIG. **15** is a plot of the output power versus input power for the optical amplifier of FIGS. **14**A–C;

FIG. **16** is a plot indicating noise figure and gain versus input power for the optical amplifier of FIGS. **14**A–C;

FIG. **17** is a plot of normalized output power versus wavelength of energy pumps optionally employed in the amplifier of FIG. **6**;

FIG. **18** is a block diagram of a data network in which the optical amplifier of FIG. **11**A may be deployed;

FIG. **19** is a block diagram of an optical transmitter, for the data network of FIG. **18**, employing the optical amplifier of FIG. **11**A;

FIG. **20** is a plot of the transmission spectrum for a single and double pass three cavity filter;

FIG. **21** is a block diagram of a pulse-shaping or pulse generating configuration;

FIGS. **22**–**23** are plots of time-domain output waveforms from a pulse-shaping element in the loss-insensitive region;

FIG. **24** is a graph of peak output power for double and single pass modulation within the loss-insensitive region, with varying delay offsets and modulation duty cycles; and

FIGS. **25**–**27** are plots of time-domain output waveforms from a saturated optical amplifier with a pulse-shaping element within the loss-insensitive region and varying offset delays.

DETAILED DESCRIPTION OF THE INVENTION

A description of preferred embodiments of the invention follows.

According to the principles of the present invention and identified by the inventor, the double-pass EDFA design has an added benefit beyond single-pass EDFA designs in that it has a loss-insensitive region, as depicted in FIG. **6**. By taking advantage of the loss-insensitive region, the double-pass design can be improved to exhibit increased stability, output power, and efficiency characteristics. Furthermore, while excess loss near the amplifier output directly reduces the output power by 1 dB per dB loss, additional attenuation in the loss-insensitive region of the double-pass amplifier has little affect on the net output power, as long as the amplifier continues to operate in saturation. The impact of attenuation in the loss-insensitive region has been measured to be less than 0.2 dB change in output power per dB of attenuation.

Consequently, advantageous elements, such as a narrow-band filter, WDM pump multiplexer(s), or other optical elements, either alone or in combination, can be inserted into the design in the loss-insensitive region with negligible power penalty at the output of the optical amplifier. For example, the narrow-band filter removes out-of-band ASE that competes with the signal for gain, enabling the amplifier to saturate at lower input power levels, as will be discussed in reference to FIGS. **10**–**12**. The narrow-band filter also makes the amplifier more stable by increasing the threshold of lasing at the ASE peak, thus reducing the risk of potentially damaging 100W class Q-switched pulses. These features make the double-pass design more robust and fault-tolerant than the single-pass equivalents.

As another example of the uses for the loss-insensitive region, a 1480/1550 nm WDM can be asserted in the loss-insensitive region to enable dual-wavelength pumping strategies with little penalty. Since the optimum erbium lengths for 1480 nm pumping are roughly twice those for 980 nm, which is a wavelength typically employed by the dual-stage energy pumps in EDFA's, this design can be driven at 980 nm, 1480 nm, or both pump wavelengths with high efficiency. A dual-wavelength design provides additional redundancy and fall-back modes of operation that are important for high-reliability in terrestrial, submarine, and free-space systems. It is particularly attractive to include 1480 nm pumping for EDFA's used in space laser communications due to radiation-induced losses in erbium-doped fiber, which are substantially higher at shorter wavelengths.

Thus, according to the principles of the present invention, a stable, high-gain, high-power, single-polarization EDFA, as herein described, provides a flexible and fault-tolerant, single-polarization, EDFA design made from commercially-available components that can be pumped using both 980 nm and 1480 nm wavelengths. Further, the commercially-available components employed in the loss-insensitive region can have higher insertion losses than those elements outside of the loss-insensitive region, and, therefore, can be less expensive optical elements. By taking advantage of the

loss-insensitive region in the double-pass design, an EDFA employing the principles of the present invention has an improved performance and stability over prior art EDFA's, such as depicted in FIG. **1**, while maintaining high efficiency and output power. FIGS. **6–19** and the descriptions associated therewith provide further details and alternative embodiments.

FIG. **6** is an embodiment of a two-stage double-pass EDFA **100***b* with a Faraday mirror **135** depicting the loss-insensitive region **600** inside the border of a rectangular box. The loss-insensitive region **600** is optically located between an optical gain medium, in this case the erbium fiber **130**, and the optical return element, in this case the Faraday mirror **135**.

The two-stage double-pass EDFA with Faraday mirror maintains single-polarization while using standard, single-mode, commercial-off-the-shelf (COTS) components. The double-pass design combines the gain of a four-stage amplifier with the efficiency of a one-stage single-pass design, as previously discussed. The loss-insensitive region (i) allows for adding optical elements to increase stability and power without sacrificing efficiency, (ii) provides flexibility in design and (iii) relaxes optical components or elements tolerances.

Notably, the optical elements asserted in the loss-insensitive region **600** can have relatively high insertion losses with respect to the optical elements external from the loss-insensitive region **600**. In particular, the optical elements external from the loss-insensitive region **600** typically have insertion losses of less than or equal to 0.2 dB, and the optical elements inside the loss-insensitive region **600** can be selected from lower-grade optical components having insertion losses of greater than 0.5 B.

In operation, the EDFA **100***b* behaves identically to the EDFA **100***a* depicted in FIG. **1**, save for the optical effects asserted by optical elements inserted into the loss-insensitive region **600**. Briefly, a polarization-maintaining optical input signal **105** is directed into a standard single-mode fiber **110** by a polarizing beam splitter **105**. A wave division multiplexer (WDM) **115** multiplexes the input signal **105** and a 980 nm pump module **605** output into an erbium fiber **130**. It should be understood that the 980 nm pump module may also include wavelength multiplexed pumps having four diode pumps, as in FIG. **1** for example. A second WDM **115** couples an output from a second 980 nm pump module **605** to a second erbium fiber **130**. Thus, the input signal **105** encounters two gain stages in a first or forward pass to the Faraday mirror **135**. The return signal from the Faraday mirror **135**, which is phase rotated 90° by two 45° phase shifts caused by the Faraday mirror **135**, makes a second or reverse pass through the two gain stages.

Following the fourth gain stage experienced by the optical signal then traveling in the reverse pass, the four-time amplified signal is directed out of the optical amplifier, indicated as an amplified single-polarization output **140***b*. It is well understood that optical amplifiers adds noise in both polarization states. Therefore, if only one polarization state is output, then only one-half of the noise is contained in the amplified single-polarization output **140***b*. Such an output is useful in fiber optic networks, since optical signals may be amplified at several points along an optical path between, say, central offices (not shown) in a telephony or ISDN network (further discussed in reference to FIG. **18**). Multiple amplifications of noise severely retards the signal-to-noise ratio of an optical signal, causing signal degradation and an increase in error rate. Therefore, a single-polarization amplifier, such as the EDFA **100***b*, can assist in maintaining high signal-to-noise ratio signals.

FIG. **7A** is a plot indicating amplified signal power in dBm versus fiber length in meters for different reflectivities of the Faraday mirror. The effects on the optical signal caused by the forward pass and reverse pass are indicated, where the forward pass begins at the lower left of the plot, at **(0,0)**, and the backward pass begins at the right side of the plot and ends at the y-axis.

Through the first erbium-doped fiber **130** in the forward pass, the optical input signal **105** increases in power from 0 dBm to between 3–5 dBm, as indicated by power curves **705**. Curves **710** show an increase through the second erbium-doped fiber **130** in the forward pass, increasing the power of the once-amplified optical signal from between 3–5 dBm to between 14–20 dBm. The loss at the Faraday mirror **135** causes the twice-amplified optical signal a reduction in power from between 14–20 dBm to between about 6–13 dBm, as indicated by arrow **715**.

In the backward pass, the second erbium-doped fiber **130** in the forward pass—and first in the reverse pass—having an increase in energy from the 980 nm pump module **605**, causes the twice-amplified optical signal to further increase in power from about 6–13 dBm to between about 21–24 dBm, as indicated by curves **720**. Finally, the first erbium-doped fiber **130** (i.e., the second erbium-doped fiber in the backward pass through the EDFA) causes the thrice-amplified optical signal to again increase in power, this time from between about 21–24 dBm to about 25–26 dBm, as indicated by curves **725**. At some point in the reverse pass, the power of the optical signal crosses the saturation threshold, Psat (FIG. **5A**), of the EDFA **100***b*.

Continuing to refer to FIG. **7A**, the first erbium fiber **130** in the embodiment of FIG. **6** in the forward pass is **15** meters in length, and the second erbium fiber **130** in the forward pass is 17 meters in length. At each stage, there are 500 mW, 980 nm pumps, where the pumps are co-propagating. The polarization-maintaining signal input **105** is 1 mW. A 1 nm filter having a 0.3 dB loss is used to filter the 1 mW input. The loss of the Faraday mirror **135** is varied, where the reflectivity is greatly changed to dramatically show how loss insensitive the loss-insensitive region **600** is, while still providing a stable output. Notably, the difference of the amplified single-polarization output **140***b* (FIG. **6**) is less than 1 dB for reflectivity changes exceeding 13 dB.

In the double-pass EDFA design, in which amplified light is reflected back through the amplifying elements, the EDFA re-uses the same gain medium, making a two stage amplifier comparable to a four-stage, single-pass design, but with fewer components in the critical path. With the double-pass design, the forward gain is equal to the backward gain, and pump power that is not converted during the forward pass can be extracted during the backward pass. When operating in saturation, the average gain adjusts over the length of the double-pass EDFA until the amplified signal extracts all the available, converted, pump power. As a result, the double-pass design is insensitive to the distribution of pump power, in contrast to single-pass designs, which are more sensitive to the pump power of the final stage.

Energy in the erbium-doped fiber **130** not released by the optical signal traveling in the forward pass tends to be released in response to the optical signal traveling in the reverse pass.

FIG. **7B** illustrates this clearly by plotting calculated output power as a function reflection loss at the Faraday mirror within the loss-insensitive region, along with a second order curve fit.

The output power (P_{out}) from an optical amplifier as a function of input power (P_{in}) is approximately described by:

$$P_{out}=P_{in}G(P_{in})=P_{in}g_o/(1+g_oP_{in}/P_{sat_out})$$

where $G(P_{in})$ is the power dependent gain, g_o is the small signal gain, and P_{sat_out} is the saturated output power. The saturated output power is the maximum power that can be delivered by the amplifier, which corresponds to ηP_{PUMP}, where η is a conversion efficiency factor and P_{pump} is the pump input power. For optical pumping, the maximum conversion efficiency η_{max}=(signal photon energy/pump photon energy)=$\lambda_{PUMP}/\lambda_{signal}$, which is ~63% for 980 nm pumped EDFA's and ~95% for 1480 nm pumped EDFA's.

Plots of P_{out} versus P_{in} and Gain versus P_{out} are shown in FIGS. **5**A and **5**B. For small input signals, the amplifier gain is high, asymptotically approaching g_o. When $g_oP_{in}<<P_{sat_out}$, the amplifier is operating in the "unsaturated" regime. Here, $P_{out}\sim g_oP_{in}$ and the output becomes a linear function of P_{in}. For large signals (i.e., $g_oP_{in}>>P_{sat_out}$), the gain becomes clamped and the output "saturated", with the output power asymptotically approaching P_{sat_out}. As long as the product of $g_oP_{in}>P_{sat_out}$, the output power becomes relatively constant, as the amplifier operates in the saturated regime. This occurs when the input power level is above the input saturation power level (P_{sat_in}), which is typically defined as the input power for which the output power is at ½ the maximum, or when,

$$P_{sat_in}=P_{sat_out}/g_o$$

Thus, high power optical amplifiers can operate in the saturated region over an extended range of input powers as long as the amplifier has high gain. For the amplifier with characteristics shown in FIGS. **7**, **8**, **11**A and **11**B, $P_{sat_out}\sim$ 400 mW or 26 dBm, $g_o\sim$50,000 or 47 dB, and therefore, $P_{sat_in}\sim$8 μW or −21 dBm. Note that in order to operate stably, the round trip gain, $G(P_{in})$ must be less than the round trip loss.

FIG. **8** is a plot of a simulated gain profile through the 500 mW, 980 nm (co-propagating) pumps at each stage. A 1 nm filter with a 0.3 dB loss filters the input signal. Similar to FIG. **7**A, simulated curves are presented for a range of Faraday mirror (FM) reflectivities, as indicated. The left set of curves **805** indicate the gain through the fiber from 0 meters to 15 meters. The gain decreases asymptotically toward zero as the optical signal approaches the end of the 15 m fiber. Similarly, at the beginning of the fiber, the set of right curves **810** have higher gain and decrease as indicated as the signal reaches the end of the 17 m fiber.

FIG. **9**A is an embodiment of the EDFA **100***c* that includes a variable attenuator **900** in the loss-insensitive region **600**. The variable attenuator **900** is used to demonstrate the trend in sensitivity of the saturated output **140***b* versus an attenuation of the optical signal caused by attenuation in the loss-insensitive region **600**.

FIG. **9**B is a plot of a measured sensitivity curve **910**, and linear regression curve **905**, of the output power in dBm versus additional attenuation in dB, as applied to the twice-amplified signal by the variable attenuator **900**. In response to the variable attenuator **900** changing in 1 dB increments from 0 db to 10 db, the output power ranges between about 24.15 dBm to about 22.0 dBm.

As indicated in the plot, the linear regression curve **905** has a slope of −0.2, indicating that the output signal **140***b* is reduced by approximately 0.2 dB for every 1 dB of attenuation in the loss-insensitive region **600**. Thus, it is possible to improve performance of the EDFA **100***b* with relatively negligible effects on the output power of the output signal **140***b* through the use of optical elements having less than optimal insertion losses.

Theoretical simulations suggest even better insensitivity to loss in the loss-insensitive region, with less than 1 dB of output power being lost for over 13 dB of additional attenuation (or reflection loss), which corresponds to less than 0.1 dB of output power reduction **140***b* for every 1 dB of attenuation in the loss-insensitive region. The simulation is shown in FIG. **7**B, which is a simulated sensitivity curve and second order fit of the output power in dBm versus additional attenuation in dB, as applied to the twice-amplified signal by the variable attenuator **900**. The simulated response in FIG. **7**B is qualitatively in agreement with the trend of the measured sensitivity in FIG. **9**B in that there is a substantial reduction of the impact of attenuation in the loss insensitive region on the output power **600**. The differences between the theoretical and measured sensitivity curves can be accounted for by the several reasons, including:

1) the attenuating device **900** used in the experiment have fiber connectors with large enough back reflections to destabilize the amplifier, resulting in the fluctuations in the data of FIG. **9**B; and
2) the lengths and characteristics of the erbium fiber, the pump power levels, and input signal levels for the experiment were different from those of the simulation, since (i) the experiment was performed on an early EDFA prototype and (ii) the simulations were performed on a later version, when more powerful pumps were available.

Nevertheless, the trends for both the theory and experiment are consistent, showing a substantial reduction of the impact of attenuation in the loss-insensitive region on the output power.

Turning now to functional aspects of employing optical elements in the loss-insensitive region, FIG. **10**A is a plot of a set of output signals **1000** across a spectrum of wavelengths as produced by the EDFA **100***a* (FIG. **1**). The set of curves is produced for input signals **105** having power levels ranging from 7.3 dBm to −8.7 dBm in 2 dBm increments.

As expected, a sharp peak **1010** is observed at the signal wavelength, which is about 1552 nm. To the left of the signal peak **1010**, however, is an unstable lasing indication **1005**, corresponding to an operational point at which the EDFA is close to oscillation. Because the set of curves range, from bottom to top, from to the highest input power, 7.3 dBm, to the lowest input power, −8.7 dBm, it should be understood that the EDFA **100***a* is most unstable when the input power of the input signal falls below a threshold, which occurs when the round trip gain (for a single polarization) approaches the round trip loss, which in this case is less than about −7 dBm.

As well known in amplifier technology, instability can cause an amplifier to self-destruct, both in electronic amplifiers and optical amplifiers. An example of an unstable optical amplifier self pulsing is shown in FIG. **10**B. In this case, the 300 mW average output power from the amplifier pulses to potentially damaging peak power levels exceeding 60W. Unstable lasing and ASE also use energy stored in the erbium-doped fiber **130** (FIG. **1**), which therefore lowers the amount of energy in the erbium fiber to be used for amplifying the optical signal, and, thus, reduces the peak **1010** of the output signal **140***a*.

In accordance with the teachings of the present invention, the EDFA **100***d* of FIG. **11**A reduces instability, observed in the 1532 nm wavelength range, through use of a narrow-

band filter optically disposed in the loss-insensitive region **600**. The narrow passband filter **1105** is centered wavelength-wise about the optical signal 1552 nm, strongly attenuating out-of-band gain and ASE noise, filtering out negative effects from the optical signal being amplified and on the EDFA **100***d* caused by unstable lasing at 1532 nm.

The gain curves of FIG. **11**B clearly depict the advantage of using the narrow-band filter **1105** to filter out wavelengths causing instability in the EDFA **100***d* (FIG. **11**A). The output is stabilized without loss in Pout despite filter losses. In particular, below −10.0 DB, the power of the output signal **140***a* of the prior art EDFA **100***a* (FIG. **1**) falls off rapidly, ending in instability, and eventually oscillation. In contrast, by employing the narrow-band filter **1105** into the EDFA **100***d* (FIG. **11**A) employing the principles of the present invention, the power output level of the output signal **140***b* is relatively constant across the 30 dB range in input power levels, most notably at low input signal **105** power levels.

Turning now to the wavelength spectrum of FIG. **12**, as compared to the plot of FIG. **10**A, two properties are clear: first, the signal peak **1210** at the amplified signal wavelength is maintained over a wide range of input power levels, and second, out-of-band ASE is suppressed over a wide dynamic range of input powers, resulting in several benefits. First, suppressing out-of-band ASE increases the lasing threshold at the ASE peak, which improves stability. Second, suppressing out-of-band ASE provides additional gain and power at the signal wavelength. Third, suppressing out-of-band ASE increases the signal-to-noise ratio to greater than 30 dB (i.e., SNR>30 dB), even at the lowest input power of the input signal. These benefits are important in that the EDFA **100***d* is insensitive to a wide range in input signal **105** power level variations.

FIG. **13** is a plot of a set of gain curves for the EDFA **100***d* for a series of pump powers for the 980 nm pump modules **605**. The input signal power producing the gain curves is kept constant. The gain curves were produced by the EDFA **100***d* using the narrow-band filter **1105** (FIG. **11**A) in the loss-insensitive region **600**. It should be understood that a band-pass filter, band-reject filter, or notch filter may be used to remove out-of-band ASE wavelengths that are detrimental to the amplification of the optical signal.

FIGS. **14**A–**14**C illustrate three stable, efficient, high-gain, high-power, single-polarization, fault tolerant optical amplifiers with slightly different power generating capability, efficiency, and redundancy.

FIG. **14**A is a block diagram of an EDFA **100***e* having dual pumping wavelengths, where a second pumping wavelength corresponding to a 1480 nm wavelength is asserted in the loss-insensitive region **600**. In this embodiment, the loss-insensitive region **600** includes a WDM **1410** coupling a 1480 nm pump module **1405** to the optical medium in the reverse pass direction. A 980 nm pump module is preferably not used because pump modules outputting the same wavelengths and facing each other cause interference with each other.

There are certain benefits to adding dual wavelength pumping to an optical amplifier, and, in particular, 1480 nm to the EDFA **100***e*. First, the EDFA **100***e* experiences an increase in output power with negligible change in efficiency. Second, the 15 m and 17 m erbium-doped fibers are nearly optimal for both 980 nm (2-stages) and 1480 nm (1-stage) pumping. Third, 1480 nm pump wavelengths are much less sensitive to radiation darkening than 980 nm, making 1480 nm pumping particularly attractive for space laser communications. Fourth, the 1480 nm pump and WDM can simply be used as a spare, providing an additional fall back mode without impacting output power or efficiency.

The amplifier in FIG. **14**B provides extra redundancy with the addition of another 980 nm WDM **1420** and a spare 980 nm pump **1415** in the loss-insensitive region **100***f*. Should the center 980 nm pump **605** fail, the spare 980 nm pump **1415** could be used with negligible impact on performance. Since the pump lasers are the least reliable elements within the amplifier, this design provides increased reliability and redundancy (of the weakest elements), with minimal impact on efficiency.

FIG. **14**C provides further redundancy with the addition of another spare 980 nm pump **1435**, and an optional 1480 nm WDM **1430** and pump **1424**, which can be used to increase output power and provide redundancy. While the addition of the redundant 980 nm pump **1435** does not impact amplifier efficiency, the additional, optional, 1480 nm WDM **1430** is in the loss-sensitive region, and, therefore, will reduce the amplifier output power and efficiency by the insertion loss of the WDM **1430**. Alternatively, the optional 1480 nm pump **1425** and associated WDM **1430** can be placed prior to the PBS **110**, removing the WDM **1430** from the loss-insensitive region **100***g*. However, in this case, the pump **1425** experiences the additional loss of the PBS **110**, which reduces the efficiency of the pump **1430**. The 980 nm pump **1435** can also be used as a primary pump source. Doing so provides an additional choice of removing the optional elements **1450** in critical path and the loss-sensitive region.

By replacing the PBS **110** with a standard or polarization-maintaining (PM) circulator, polarization independent performance can be attained. Also, while shown here for single mode pumping, cladding pumped designs can be used with the double-pass configuration as well, to achieve a stable, high-gain, high power amplifier.

The WDM **1410** typically has an insertion loss of 0.1 dB. Thus, using the linear regression curve **905** (FIG. **9**B), the loss at the output is 0.02 dB, translating into about a 2% loss in the double pass design. Additionally, the 1480 nm pump module provides high reliability by providing a redundancy for amplifying the optical signal.

FIG. **15** provides curves **1505**, **1510**, and **1515** illustrating the increase in gain and redundancy provision resulting from including a 1480 nm pump module **1405** (FIGS. **14**A–C) in the loss-insensitive region of the EDFA **100***e* (FIG. **14**A). Using the 1480 nm pump module only, the EDFA **100***e* produces an output power of about 260 mW for an input power ranging from −9.0 dBm to +10 dBm. Employing a 980 nm pump module only, the EDFA **100***e* produces an output curve **1510** of about 520 mW across the input power range. Employing both the 980 nm and 1480 nm pumps, the EDFA **100***e* produces an output power curve **1515** of about 800 mW across the input power range. Thus, the output power achieved by employing both wavelength pumps is additive, but also provides the benefit of redundancy.

FIG. **16** is a plot relating gain and noise figure in dB to the input power in dBm of the polarization-maintaining input signal **105** (FIG. **6**). A noise figure curve **1605** ranges from 12 dB to 16 dB in a positive parabolic shape having a minimum slightly above 9 dB. The gain data points **1610** are linear with very little variance. Feeding a standard linear regression algorithm with the gain data points **1610** produces a linear regression gain curve **1615** ranging from about 42 dB to about 14 dB in a linear, negative slope. It should be understood that a relatively high noise figure is expected for high-gain, high-power EDFA's, such as the EDFA **100***e*.

FIG. **17** is a plot indicating a normalized output power in dB/0.1 nm versus wavelengths between 960 nm and 1000

nm having a measured 980 nm QUAD-pump module (QPM). The quad-pump module is the dense wavelength division multiplexer (DWDM) **120** (FIG. **1**) combining four grating-stabilized pump lasers **125** (FIG. **1**). Each pump delivers approximately 150 mW at approximately 980 nm. An advantage of using the dense wavelength division multiplexer with four diode pumps is to provide a redundant source of 600 mW pump power, providing graceful, fault tolerant degradation. The EDFA **100***e* (FIG. **14**A) can employ the DWDM generating the output spectrum of FIG. **17**. Similarly, in the loss-insensitive region **500**, a DWDM having similar qualities in the 1480 nm range can be introduced.

FIG. **18** is a block diagram of an example data network **1800** employing fiber-optic interconnections and subsystems to transmit content across the network **1800**. The network **1800** includes a content provider server **1805**, optical switches **1810**, the Internet **1815**, and a client **1820**. The content provider server **1805** includes an optical transmitter **1825**, which employs the optical amplifier **1100**, as described in FIGS. **6–17**. The optical switches **1810** include an optical receiver (not shown) and optical amplifiers (not shown), preferably employing the principles of the present invention. Further, the content provider server **1805** also includes an optical receiver (not shown). Finally, the client **1820** also includes an optical receiver (not shown) and optical transmitter (not shown). The optical switches **1810** are deployed about a telephony network or the Internet. Central offices (not shown) are good places for deployment of the optical transmitters and receivers in such networks.

Most sources in modulators provide single polarization output. Free space systems typically use single polarization amplifiers; however, commercial systems typically do not use single polarization amplifiers because fiber tends not to preserve polarization, even though single polarization amplifiers generate less noise as a result of providing amplified noise in a single polarization, as opposed to two polarizations (i.e., one-half the noise), as discussed above.

It is well-known in fiber communication systems to have single polarization in receiver amplifiers for better performance, but not in the transmitting amplifiers. In such a case, a non-polarization-maintaining, conventional, fiber amplifier is followed by a polarizer. However, in the fiber amplifier and polarizer combination prior art arrangement, the polarizer must be carefully controlled to ensure maximum power passes through it. The polarizer is controlled to track the polarization of the output from the master oscillator. In this way, the polarizer allows maximum energy to pass to the optical fiber network, and, hence, to the receiver at the other end. The polarization-maintaining embodiment of the present invention obviates the need for such polarizers and polarization control.

FIG. **19** is a block diagram of the example optical transmitter **1825**. The optical transmitter **1825**, as described in U.S. patent application Ser. No. 09/261,628, the entire teachings of which are incorporated herein by reference, includes a source **1905**, which typically provides a polarized output, a modulator **1910**, which encodes data onto the optical signal, and the EDFA **1100**, employing the principles of the present invention and providing a single-polarization output. Using the EDFA **1100**, the 1550 nm optical signal remains polarized from the source **1905** through the EDFA **1100** and onto the network data path **1915** without the assistance of a polarizer.

As discussed above, using the EDFA **1100** provides only half of the noise as would be put onto the signal were it to have both polarizations (i.e., TE and TM modes). Therefore, although the fiber of the network data path **1915** tends not to maintain polarization, for signal-to-noise ratio reasons, there is some benefit to using the EDFA **1100** providing a single-polarization output. Again, since adding and amplifying noise is cumulative, providing multiple single-polarization EDFA's **1100** across the network **1800** (FIG. **18**) controls the signal-to-noise ratio of signals, thereby reducing bit-rate errors between devices communicating across the network, such as from content provider servers **1805** to clients **1820** (FIG. **18**).

Since light of both orthogonal polarizations pass through the erbium fiber, gain and, hence, the noise contribution is the same in both polarization states. In addition, by passing through each element twice, the effects of such elements are enhanced, as shown in FIG. **20** for a three cavity, thin film, transmission filter.

Referring now to FIG. **20**, the net transfer function for a single pass through the transmission filter is $T_{sp}(\lambda)$ **2010**, and the net transfer function for the double pass is $T_{dp}(\lambda)=T^2_{sp}(\lambda)$ **2020**. This makes it easier to produce narrow bandpass filters with very good rejection bands **2030**, **2040**, since a filter with x=15 dB attenuation in the single pass—which is relatively easy and inexpensive to fabricate—will produce 2x=30 dB attenuation for the double pass.

Double-pass filters generate waveforms that are more symmetric than single-pass filters. For example, pending U.S. patent application Ser. No. 09/261,628, filed on Mar. 3, 1999, entitled "Variable-Rate Communication System with Optimal Filtering," by Caplan et al., the entire teachings of which are incorporated herein, describes a Symmetric Filtering (SF) approach that can be used with quasi-symmetric waveforms that lead to improved communications performance. So, by inserting the double-pass filters into the loss-insensitive region **600** (FIG. **6**), the benefits of the symmetric filtering approach can be taken advantage of with essentially no performance penalty.

There are also benefits for using direction-independent modulating devices, such as electro-absorptive modulators in the double-pass LIR. As shown in FIGS. **21–27**, using such devices in the LIR (i) can improve the extinction ration (ER) and (ii) reduce or adjust the transmitted pulse width or shape when generating or shaping a return-to-zero (RZ) pulse stream. FIGS. **21** and **22** show that by varying a delay element in the LIR, the pulse width of the amplified output waveform can be adjusted to generate the waveforms shown in FIGS. **23–27**.

FIG. **21** shows a pulse-shaping or pulse generating configuration **2100** that can be used in the LIR for applications such as improving extinction ratio, pulse shaping, generating variable pulse widths or peak power levels, or complete 3R (re-amplification, regeneration, and resynchronization). This setup can function in a single or double pass configuration if the modulator **2110** is direction dependent (e.g., a traveling wave Mach-Zehnder modulator) or direction independent (e.g., an electro-absorption modulator (EAM)).

In the direction independent case, the modulator **2110** can be driven by a periodic pulsed waveform **2120** with a frequency equal to 1/T, where T is the symbol period in the transmitted data stream. Phase and frequency can be controlled with an optional feedback or feedforward control element **2130**. An adjustable delay element **2040**, located after the modulator **2110**, is used to control the round-trip delay to an integer multiple of the symbol period plus an offset ($\tau_{offset}/2$), such that the net round trip delay is $mT+\tau_{offset}$, where m is an integer. The adjustable delay element can also be controlled by feedback or feedforward control elements to achieve desired pulse width, shape, or

timing. Furthermore, this active approach can be combined with a plurality of other filtering/shaping techniques to achieve a desired waveform.

FIG. **22** illustrates the effect of double-pass modulator pulse shaping for a fixed 30% offset and a 10 dB modulator extinction ratio (ER). A single-pass transmission **2200** with a 10 dB ER **2205** returns to the modulator with a 30% offset, as shown by a double-pass transmission input **2220**. A double pass transmission output **2240** has a reduced pulse width and (i) an improved extinction 20 dB ER **2245** outside of the overlap and (ii) a 10 dB ER **2250** within the 30% offset.

FIG. **23** illustrates the effect of double-pass modulator pulse shaping for varying offset delays and a 15 dB modulator extinction ratio. The 0% offset waveform **2305** has retained its basic single-pass shape and pulse width, but has an improved 30 dB ER. In contrast, the 80% offset waveform **2306** has a substantially reduced pulse width, but little improvement in ER.

FIG. **24** shows the calculated output peak power from the saturated (average power limited) amplifier for double- and single-pass modulation with varying offsets and duty-cycles. The expression for the peak double-pass power is given by:

$$P_{peak,double\ pass} = \frac{P_{average}[\mathrm{LIR_IL}(\tau_{offset})]}{\mathrm{DC} * (1 - \tau_{offset} + 2 * \tau_{offset} * ER) + (1 - \mathrm{DC} * \tau_{offset}) * ER^2}$$

and the expression for the peak single-pass power is given by:

$$P_{peak,single\ pass} = \frac{P_{average}[\mathrm{LIR_IL}(\tau_{offset})]}{\mathrm{DC} + (1 - \mathrm{DC}) * ER}$$

where LIR_IL is the insertion loss within the loss-insensitive region, which is a function of τ_{offset}, and $P_{average}$ is the average saturated output power, which is a weak function of LIR_IL, shown in FIG. **7**B. For a modulator with a 3 dB single-pass insertion loss and a 10 dB ER, normalized peak output power asymptotically approaches 10 dB (~ER) for the single-pass case, whereas it approaches 20 dB (~ER^2) for the double-pass case. Moreover, the double-pass configuration can produce higher peak power levels **2410** by varying the offset time delay.

FIG. **25** shows the saturated amplifier output waveforms for adjustable pulse width and peak output power for a duty-cycle DC=½, ER=−15 dB, and varying offset delays normalized to a percentage of maximum pulse width. FIGS. **26** and **27** show the same, but for DC=¼ and ⅛, respectively, with peak power levels reaching as high as 29 times the average. Note that, while approximately square waveforms were shown here for the purposes of illustration, other pulse shaping waveforms (such as approximately Gaussian or hyperbolic secant pulses) can be applied in a similar manner.

Such capabilities can be used to actively optimize overall system performance. For instance, if intersymbol interference (ISI) were a limiting factor at the end of a communication link, the pulses can potentially be narrowed at upstream amplifier/regeneration node or nodes; whereas, if nonlinear effects dominate, the pulses, for example, could possibly be broadened in time to reduce peak power levels, (as shown in FIGS. **24**–**27**), since the optical amplifier of this invention is predominantly average power limited (APL). Consequently, a high-gain EDFA directly expands the functional range of transmission rates for variable duty-cycle, multi-rate, optical communication systems, as discussed in Caplan et al., "High-sensitivity variable-rate transmit/receive architecture", IEEE Leos '99, TuU 0003, 1999 and pending U.S. patent application Ser. No. 09/261,628, filed on Mar. 3, 1999, the entire teachings of both are incorporated herein by reference.

Direction dependent intensity and phase modulators, such as traveling wave devices, can be used to modify the waveform, as well. Despite making two passes through such a device, only one pass sees the effect of such a modulator. Consequently, these devices can be incorporated into the LIR to reshape, retime, and so forth without constraints on the round trip time delay from the back-reflecting element. While there is no benefit of enhanced double-pass ER, periodic or non-periodic waveforms can be used to shape the transmitted signals or directly impart data on the transmitted signal.

In addition, specialty fibers (such as DCF, DSF, etc.) are typically expensive compared to standard telecom fibers. Since the effect of these fibers (and cost) are a function of their length, significant savings (in both cost and packaging/handling expense) can be realized by incorporating them in the loss-insensitive double pass design, which can achieve a desired goal with essentially half the fiber with little or no impact on the amplifier output power.

In summary, the double-pass benefits for using pulse or spectral shaping elements in the loss-insensitive region include:

1. elimination of polarization dependent loss (PDL) sensitivity;
2. enhancement of transfer functions providing better rejection or extinction ratio with less expensive, easier to manufacture elements;
3. provision of capability for adjustable pulse shaping, variable pulse widths, and peak power levels;
4. useful as a pulse shaper or generator in single or double-pass configurations, depending on the direction dependence of the modulator;
5. generation of more symmetric waveforms in time, so can be used for symmetric filtering (SF); and
6. allowance for less specialty fiber needed for dispersion compensation or nonlinear switching.

While this invention has been particularly shown and described with references to preferred embodiments thereof, it will be understood by those skilled in the art that various changes in form and details may be made therein without departing from the scope of the invention encompassed by the appended claims.

It should be understood that although the preferred embodiment of the EDFA (e.g., EDFA **1100**) provides a single-polarization output, the principles of the present invention also support an optical amplifier embodiment having a non-polarized output. One such way to provide the EDFA without a polarized output is to use a non-polarizing beam splitter or a circulator, which allows a signal to enter the EDFA in the forward pass and the amplified signal to exit the EDFA from the reverse pass without being polarized by an optical element of the EDFA.

Although shown as a band-pass filter, the optical element in the loss-insensitive region may be, or include, at least one of the following filters: band-reject filters, notch filters, comb filters or other pulse shaping elements than can be used in optical networks. The band-reject filter and/or notch filter are employed to reduce the ASE, as indicated in FIGS. **10**A and **10**B. The comb filter is typically employed for wavelength division multiplexing systems, which service multiple data signals at multiple wavelengths in a multi-

plexing manner. Such a filter can pass (or shape) multiple signal wavelengths while attenuating out-of-band ASE noise.

Pulse shaping elements are typically employed to compensate for effects such as fiber dispersion, nonlinearities, or accumulated noise, but could also be used to generate a particular waveform that improves net communication performance in the presence of one or more such effects. Such an element or elements could be a specialized transmission filter, or a type of fiber such as dispersion compensating fiber (DCF), dispersion shifted fiber (DSF), small core fiber which can increase nonlinear effects, or a combination of such elements. Also, pulse shaping elements, such as saturable absorbers, modulators, and nonlinear optical switches, which directly modify the waveform in time, can be added for applications including all-optical re-amplification, regeneration, and retiming (3R) signal processing in place of costly optical-to-electronic-optical (OEO) conversion.

All optical wavelength converters can also be employed in the loss-insensitive region (LIR). Such elements can be used to route optical signals, shift wavelength(s) in cases of conflict within an optical network, and perform spectral inversion, which can be used to combat the effects of fiber dispersion and nonlinearities. Although current wavelength converters presently have poor conversion efficiency of about −7 dB, they can be used within the LIR with less than 0.5 dB power penalty at the amplifier output, according to the simulations of FIG. **7**B. And, since the signal makes a double pass (in orthogonal polarizations) through elements in the loss-insensitive region of the optical amplifier of this invention, power variation due to polarization dependent loss (PDL) of these elements is eliminated. This benefit extends outside of the LIR, as well, eliminating effects such as polarization hole burning in the erbium fiber.

Also, the preferred embodiments generally describe single-mode erbium-doped fiber as the gain medium pumped by single-mode pumps that are coupled, using single-mode coupling elements, to the erbium fiber. It should be understood that the scope of the present invention does not restrict the gain medium to being single-mode erbium-doped fiber. The principles of the present invention work with multimode gain media and cladding pumped designs, in which case, the wavelength(s) or type of the pump(s) (single or multi-mode) may be selected to be an alternative wavelength to provide maximum energy transfer to the alternative gain medium.

Also, the length of the gain medium described herein is generally about 15 m to about 17 m, which is nearly optimum for two 500 mW, 980 nm wavelength multiplexed QPM's (quad pump modes) pumping Lucent® HP980 type erbium fiber. However, the length of the fiber may be optimized for the 980 nm pump wavelength(s) or the 1480 nm pump wavelength(s), as well as pump and signal power levels, type of gain medium, or pumping configuration. Additionally, the gain medium may be selected to have a length suitable for another wavelength should a third pump wavelength be selected or should different doping concentrations or materials be implanted in the same or different gain medium. It should be understood that the principles of the present invention extend to optical amplifiers beyond the EDFA embodiment described herein.

What is claimed is:

1. An optical amplifier, comprising:

an amplifying optical path of elements of low insertion losses including a non-lasing optical gain medium through which an optical signal is amplified;

an optical return path by which amplified light from a first pass returns through the gain medium in a reverse pass through the gain medium; and

at least one optical element in the optical return path between the forward pass and the reverse pass having a loss substantially greater than the insertion losses of the elements of the amplifying optical path;

the optical amplifier operating in saturation and being substantially non-lasing.

2. The optical amplifier according to claim **1**, wherein the elements in the amplifying optical path have insertion losses less than about 0.5 dB.

3. The optical amplifier according to claim **2**, wherein the elements in the amplifying optical path have insertion losses less than about 0.2 dB.

4. The optical amplifier according to claim **1**, wherein said at least one optical element between the forward pass and the reverse pass has a loss of greater than 0.5 dB.

5. The optical amplifier according to claim **1**, further including an input element coupling the optical signal to the amplifying optical path of elements, wherein the input element is selected from a group consisting of: a beam splitter, polarizing beam splitter, or circulator.

6. The optical amplifier according to claim **1**, wherein the gain medium includes an erbium-doped fiber.

7. The optical filter according to claim **1**, further including at least one energy pump coupled to the gain medium.

8. The optical amplifier according to claim **7**, wherein said at least one energy pump includes an energy pump outputting a signal of about 980 nm wavelength.

9. The optical amplifier according to claim **7**, wherein said at least one energy pump includes an energy pump outputting a signal of about 1480 nm wavelength.

10. The optical amplifier according to claim **7**, further including multiple spare energy pumps.

11. The optical amplifier according to claim **1**, wherein the gain medium is about 15 meters in length.

12. The optical amplifier according to claim **1**, wherein said at least one optical element between the forward pass and the reverse pass includes at least one of the following filters: band pass filter, band reject filter, notch filter, or comb filter.

13. The optical amplifier according to claim **1**, wherein said at least one optical element between the forward pass and the reverse pass includes at least one of the following optical elements: pulse shaper, specialty fiber, nonlinear optical element, dispersion compensating element, direction independent modulator, direction dependent modulator, optical delay element, optical switch, wavelength converter, pump coupling element or wavelength division multiplexer coupling at least one energy pump outputting a signal of about 1480 nm wavelength or 980 nm wavelength to a gain medium in the optical return path.

14. The optical apparatus according to claim **1**, wherein said at least one optical element includes an optical return element selected from a group consisting essentially of: a mirror, Faraday mirror, polarization rotation reflection element, beam splitter and plural mirrors, or continuous optical medium loop.

15. The optical amplifier according to claim **1**, wherein the round-trip gain of the optical signal does not equal the round-trip loss of the optical signal.

16. The optical amplifier according to claim **1**, wherein:

the amplifying optical path of elements includes:

a first WDM, coupled to the non-lasing optical gain medium, inserting into the non-lasing optical gain medium a signal of about 980 nm wavelength from a first energy pump;

a second WDM, coupled to a second non-lasing optical gain medium, inserting a into the second non-lasing

optical gain medium a signal of about 980 nm wavelength from a second energy pump;

said at least one optical element, having a loss substantially greater than the insertion losses of the amplifying optical path, passes essentially the optical signal and includes a Faraday mirror; and

said at least one optical element further including a third WDM, optically disposed between the forward pass and the reverse pass, inserting into the second and first optical gain media energy of about 1480 nm wavelength from a third energy pump.

17. The optical amplifier according to claim **1**, wherein the optical signal, having been amplified, is substantially singularly polarized.

18. The optical amplifier according to claim **17**, wherein the polarization state of the optical signal, having been amplified, is independent of the polarization state of the input.

19. The optical amplifier according to claim **1**, wherein the optical element in the optical return path between the forward pass and the reverse pass restricts the optical signal to wavelengths of interest to prevent other wavelengths from lasing.

20. The optical amplifier according to claim **1**, used in a free-space application.

21. The optical amplifier according to claim **1**, used in a fiber network application.

22. The optical amplifier according to claim **1** wherein the amplified optical signal exiting the reverse path is at least about 200 mW.

23. The optical amplifier according to claim **1** having an efficiency of at least about 15%.

24. A method for amplifying an optical signal, comprising:

amplifying, through a non-lasing optical gain medium, the optical signal through an amplifying optical path of elements of low insertion losses including the non-lasing optical gain medium;

redirecting the amplified optical signal from a first pass through the gain medium to a reverse pass through the gain medium;

engaging the amplified optical signal with at least one optical element, between the forward pass and the reverse pass, having a loss substantially greater than the insertion losses of the amplifying optical path; and

the amplifying occurring in saturation and being substantially non-lasing.

25. The method according to claim **24**, wherein the elements in the amplifying optical path have insertion losses less than about 0.5 dB.

26. The method according to claim **25**, wherein the elements in the amplifying optical path have insertion losses less than about 0.2 dB.

27. The method according to claim **24**, wherein said at least one optical element between the forward pass and the reverse pass has a loss of greater than 0.5 dB.

28. The method according to claim **24**, further including directing the optical signal to the amplifying optical path of elements via an input element, wherein the input element is selected from a group consisting of: a beam splitter, polarizing beam splitter, or circulator.

29. The method according to claim **24**, wherein the gain medium includes an erbium-doped fiber.

30. The method according to claim **24**, further including coupling at least one energy pump to the gain medium.

31. The method according to claim **30**, wherein said at least one energy pump includes an energy pump outputting a signal of about 980 nm wavelength.

32. The method according to claim **30**, wherein said at least one energy pump includes an energy pump outputting a signal of about 1480 nm wavelength.

33. The method according to claim **30**, further including multiple spare energy pumps.

34. The method according to claim **24**, wherein the gain medium is about 15 meters in length.

35. The method according to claim **24**, wherein said at least one optical element between the forward pass and the reverse pass includes at least one of the following filters: band pass filter, band reject filter, notch filter, or comb filter.

36. The method according to claim **24**, wherein said at least one optical element between the forward pass and reverse pass includes at least one of the following optical elements: pulse shaper, specialty fiber, nonlinear optical element, dispersion compensating element, direction independent modulator, direction dependent modulator, optical delay element, optical switch, wavelength converter, pump coupling element or wavelength division multiplexer coupling at least one energy pump outputting a signal of about 1480 nm wavelength or 980 nm wavelength to a gain medium in the optical return path.

37. The method according to claim **24**, wherein said at least one optical element includes an optical return element selected from a group consisting essentially of: a mirror, Faraday mirror, polarization rotation reflection element, beam splitter and plural mirrors, or continuous optical medium loop.

38. The method according to claim **24**, wherein the round-trip gain of the optical signal does not equal the round-trip loss of the optical signal.

39. The method according to claim **24**, further including:

inserting into the non-lasing optical gain medium a signal of about 980 nm wavelength from a first energy pump;

inserting a into a second non-lasing optical gain medium a signal of about 980 nm wavelength from a second energy pump;

passing essentially only the frequency of the optical signal;

inserting a signal of about 1480 nm wavelength from a third energy pump, optically disposed between the forward pass and the reverse pass, into the second and first optical gain media.

40. The method according to claim **24**, wherein the optical signal, having been amplified, is substantially singularly polarized.

41. The method according to claim **24**, wherein the polarization state of the optical signal, having been amplified, is independent of the polarization state of the input signal.

42. The method according to claim **24**, wherein engaging the amplified optical signal with at least one optical element between the forward pass and the reverse pass includes restricting the amplified optical signal to wavelengths of interest to prevent other wavelengths from lasing.

43. The method according to claim **24**, used in a free-space application.

44. The method according to claim **24**, used in a fiber network application.

45. The method according to claim **24** wherein the amplified optical signal exiting the reverse path through the gain medium is at least about 200 mW.

46. The method according to claim **24** wherein amplifying the optical signal is at least about 15% efficient.

47. An optical amplifier, comprising:

an input/output element (i) receiving an optical signal and directing the optical signal in a forward path composed

of a gain medium having a low insertion loss, and (ii) receiving the amplified optical signal and directing the amplified optical signal away from the gain medium;

an energy pump adding energy to the gain medium along the fiber, the optical signal being amplified by interacting with the added energy;

a reversal element directing the amplified signal in a reverse path in the optical fiber for a second amplification by interacting with the added energy; and

an optical element in addition to the optical fiber and having a loss substantially greater than the insertion losses of the elements of the forward and reverse paths, the optical element stabilizing the optical signal to achieve saturation (i) for a greater range of given input power levels of the optical signal than without the optical element and (ii) without significantly reducing the overall output power of the optical amplifier;

the optical amplifier operating in saturation and being substantially non-lasing.

48. The optical amplifier according to claim **47** wherein the amplified signal exiting the reverse path is at least about 200 mW.

49. The optical amplifier according to claim **47** having and efficiency of at least about 15%.

50. An optical amplifier, comprising:

a high-gain high-power optical assembly comprising:

a first optical director element directing an optical signal in a forward direction in an optical transmission medium having low insertion loss, the optical transmission medium comprising energy absorbing matter, at least one optical pump coupled to the optical transmission medium to increase an energy state of at least a portion of the optical transmission medium; and

a second optical director element redirecting the optical signal in a reverse direction in the optical transmission medium back to the first optical director element to be directed by the first optical director element in an outward direction from the optical medium, the optical signal being amplified in both the forward and reverse directions by the increased energy state of the portion of the optical medium, the optical signal at an output of the optical medium having a power level corresponding to a saturation range for the optical amplifier, the saturation range being achieved for a given power range of the optical signal received by the first optical director element; and

a stability extender optically disposed between the optical transmission medium and the second optical director element and having a loss substantially greater than insertion losses of the optical transmission medium, the stability extender reducing amplified spontaneous emission at wavelengths other than about the wavelength of the optical signal to extend the range of power of the optical signal at which the amplifier output is saturated;

the optical amplifier operating in saturation and being substantially non-lasing.

51. A method for extending stability of a high-gain, high-power optical amplifier, the method comprising:

directing an optical signal into an optical transmission medium, having low insertion loss, in a forward direction;

redirecting the optical signal back through the optical transmission medium in a reverse direction;

amplifying the optical signal in the optical transmission medium in each direction such that the twice-amplified optical signal achieves saturation for a given range of power levels of the unamplified optical signal;

between directing and redirecting, filtering the optical signal, through use of an optical element having a loss substantially greater than insertion loss of optical transmission medium, to extend the given range of power levels of the optical signal for which the twice-amplified optical signal achieves saturation; and

outputting the twice-amplified optical signal from the optical transmission medium;

the amplifying occurring in saturation and being substantially non-lasing.

52. An apparatus for optically amplifying an optical signal, comprising:

means for directing an optical signal into an optical transmission medium, having low insertion loss, in a forward direction;

means for redirecting the optical signal back through the optical transmission medium in a reverse direction;

means for amplifying the optical signal in the optical transmission medium in each direction such that the twice-amplified optical signal achieves saturation for a given range of power levels of the unamplified optical signal;

between said means for directing and said means for redirecting, means, having a loss substantially greater than insertion losses of the directing means and optical transmission medium, for filtering the optical signal to extend the range of power levels of the optical signal for which the twice-amplified optical signal achieves saturation; and

means for outputting the twice-amplified optical signal from the optical transmission medium;

the apparatus operating in saturation and being substantially non-lasing.

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